

# **Neutrino Factory Acceleration Scenarios**

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NFMCC Collaboration Meeting  
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# Outline



- Description of the acceleration schemes (neutrino factory)
- Recent work on the RLA
- Tracking in linear non-scaling FFAGs
- Electron model for linear non-scaling FFAG (EMMA)
- Analysis of the NuFactJ FFAG scheme
- Analysis of an isochronous FFAG
- New bunch train scenario

# Acceleration Schemes

## List of Schemes



- The Study IIa scheme
- Isochronous FFAGs
- Scaling FFAGs

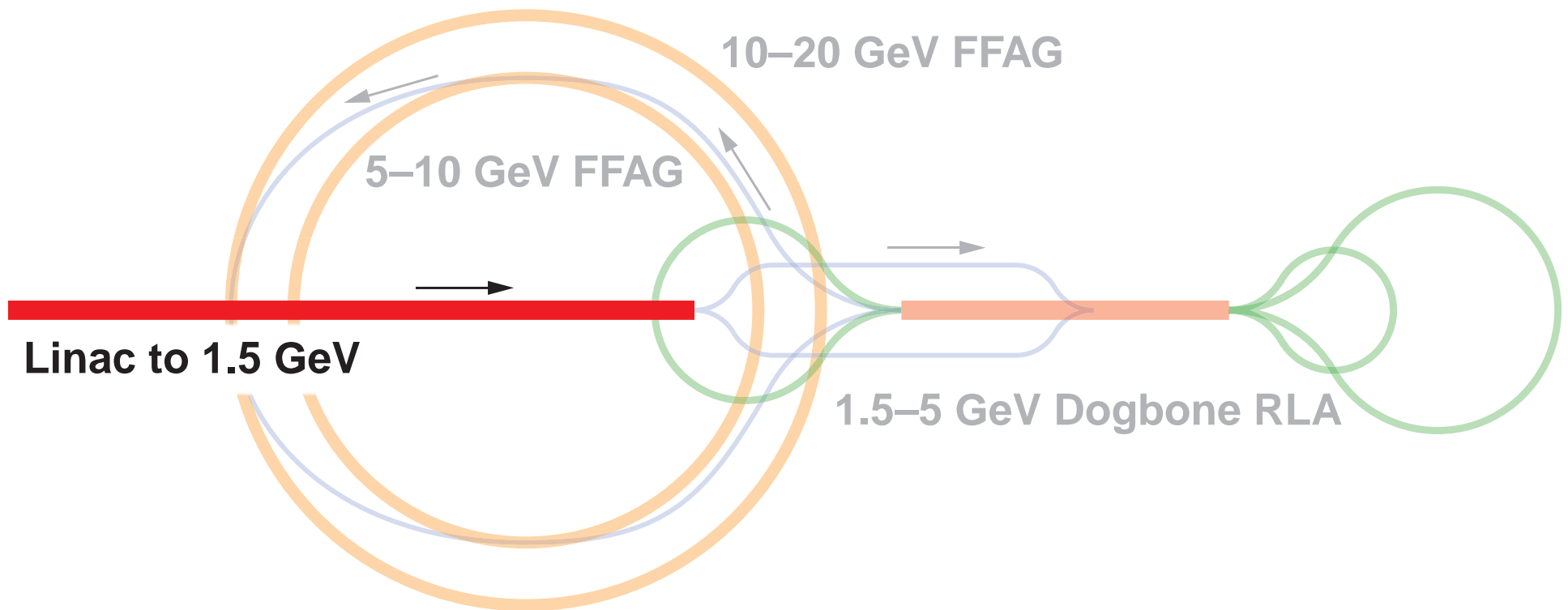
# Acceleration Schemes

## The Study IIa Scheme



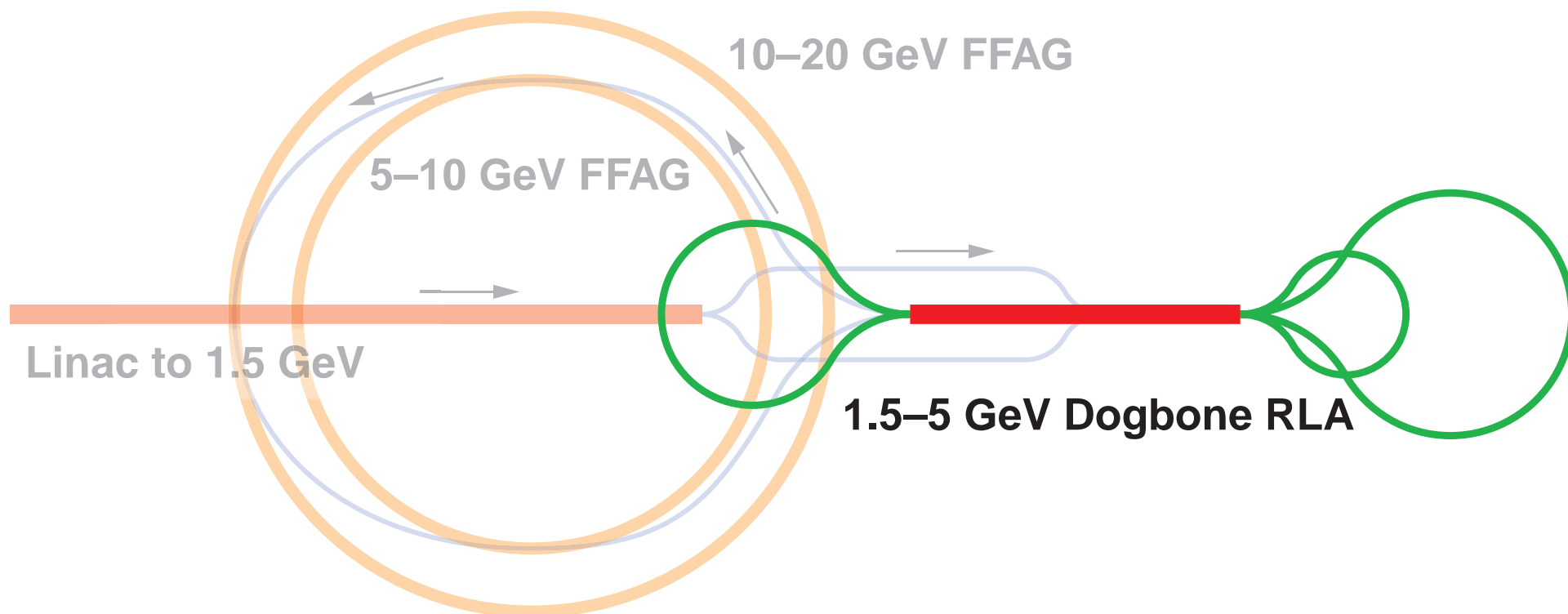
- Linac from cooling to 1.5 GeV
- Dogbone RLA from 1.5 GeV to 5 GeV
- Linear non-scaling FFAG from 5 GeV to 10 GeV
  - ◆ Save money by more efficient use of the RF
- Linear non-scaling FFAG from 10 GeV to 20 GeV

# The Study IIa Scheme Linac



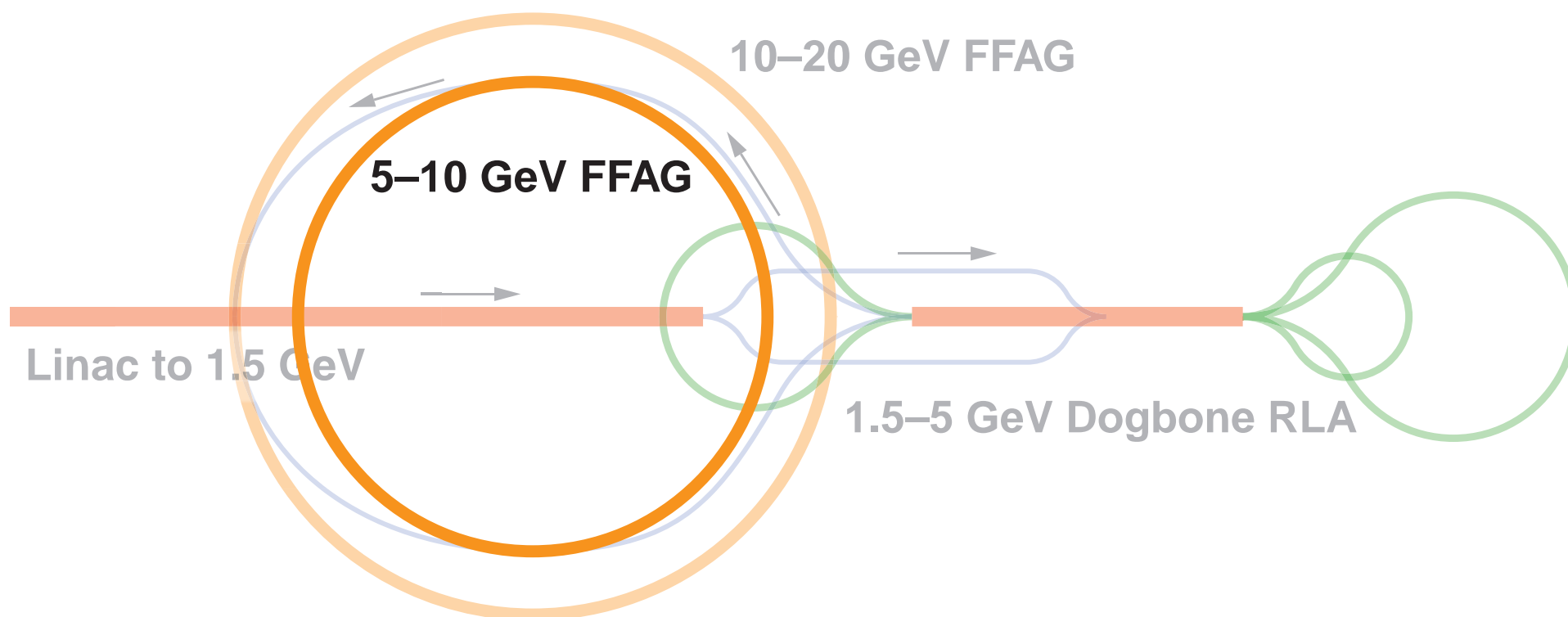
# The Study IIa Scheme

## Dogbone RLA



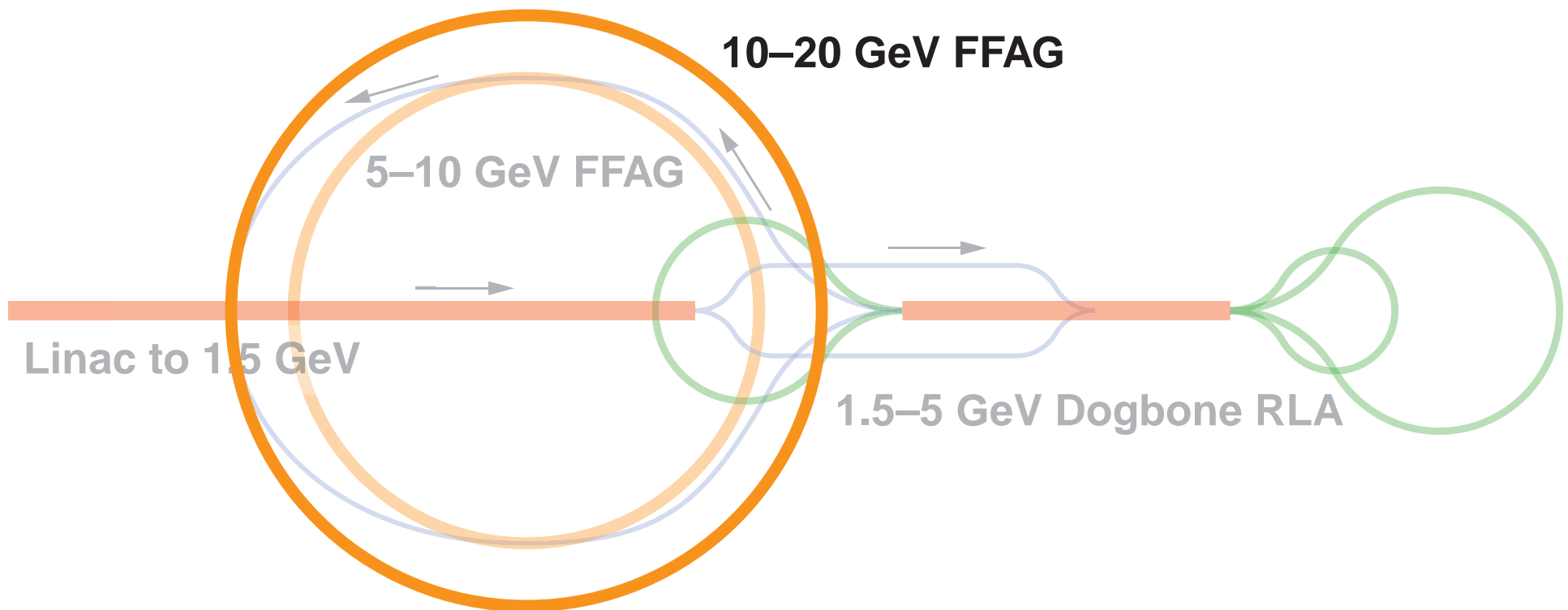
# The Study Ila Scheme

## 5–10 GeV FFAG

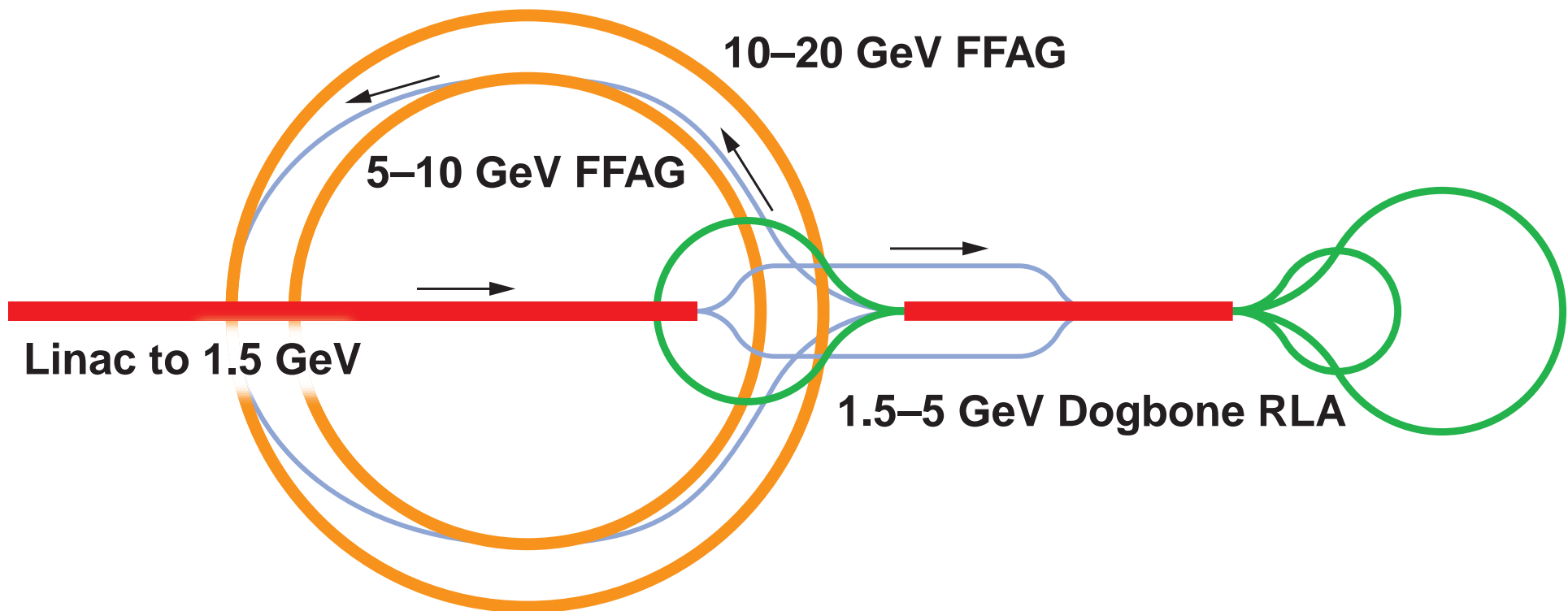


# The Study Ila Scheme

## 10–20 GeV FFAG



# The Study IIa Scheme



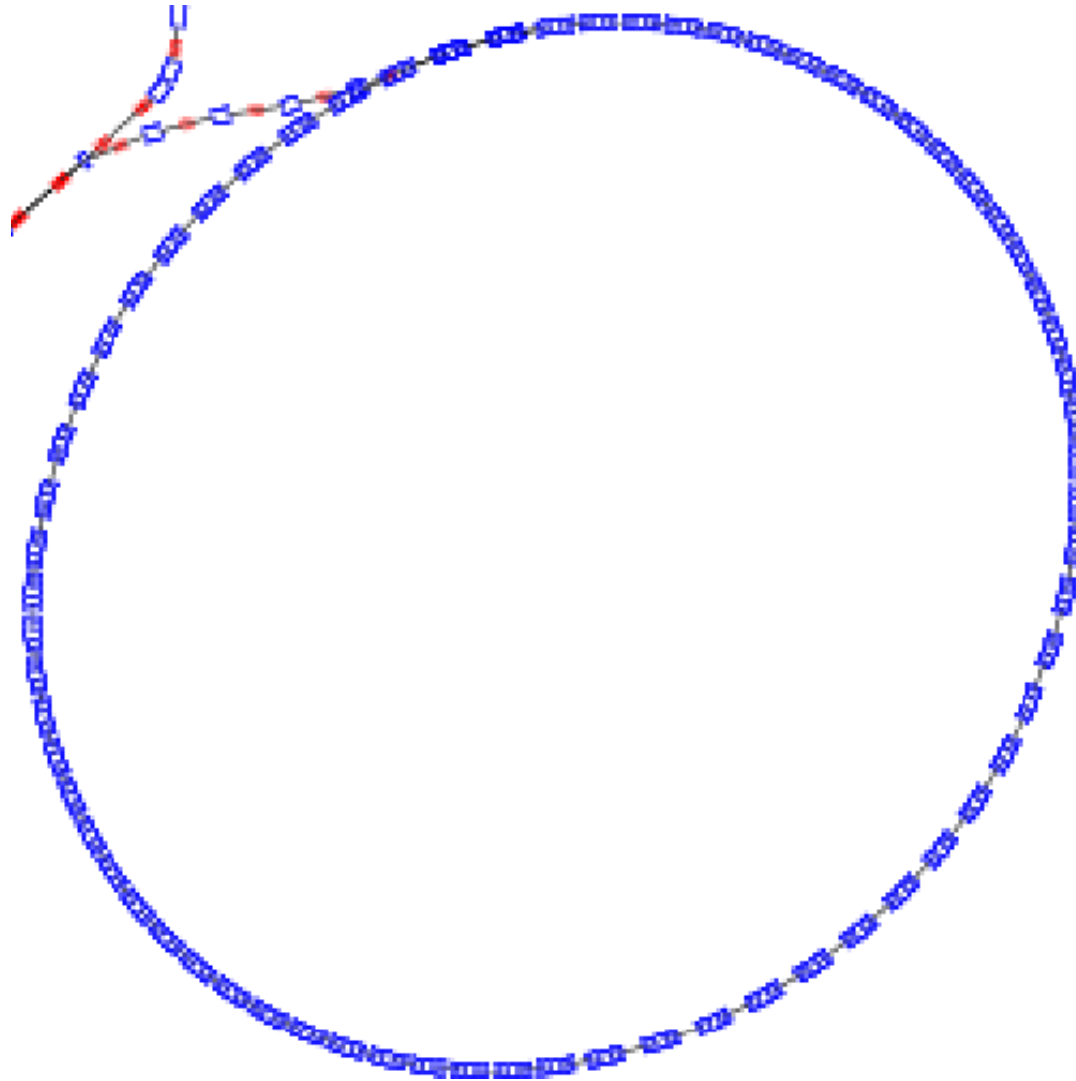
# Acceleration Schemes

## Isochronous FFAGs



- Replace the FFAGs in the NFMCC scheme with “isochronous FFAGs”
- Linear non-scaling FFAGs have a time of flight that depends on energy
  - ◆ Difficult to keep bunch synchronized with the RF
  - ◆ Puts a lower limit on the required voltage
- Use nonlinear magnets to make the FFAG isochronous over the entire energy range
  - ◆ May limit dynamic aperture
  - ◆ Will analyze a bit later
- Can also use two types of cells: longer cells with RF, shorter cells without
  - ◆ Can reduce machine cost
  - ◆ Need to match between

# Isochronous FFAGs with Insertions



# Acceleration Schemes

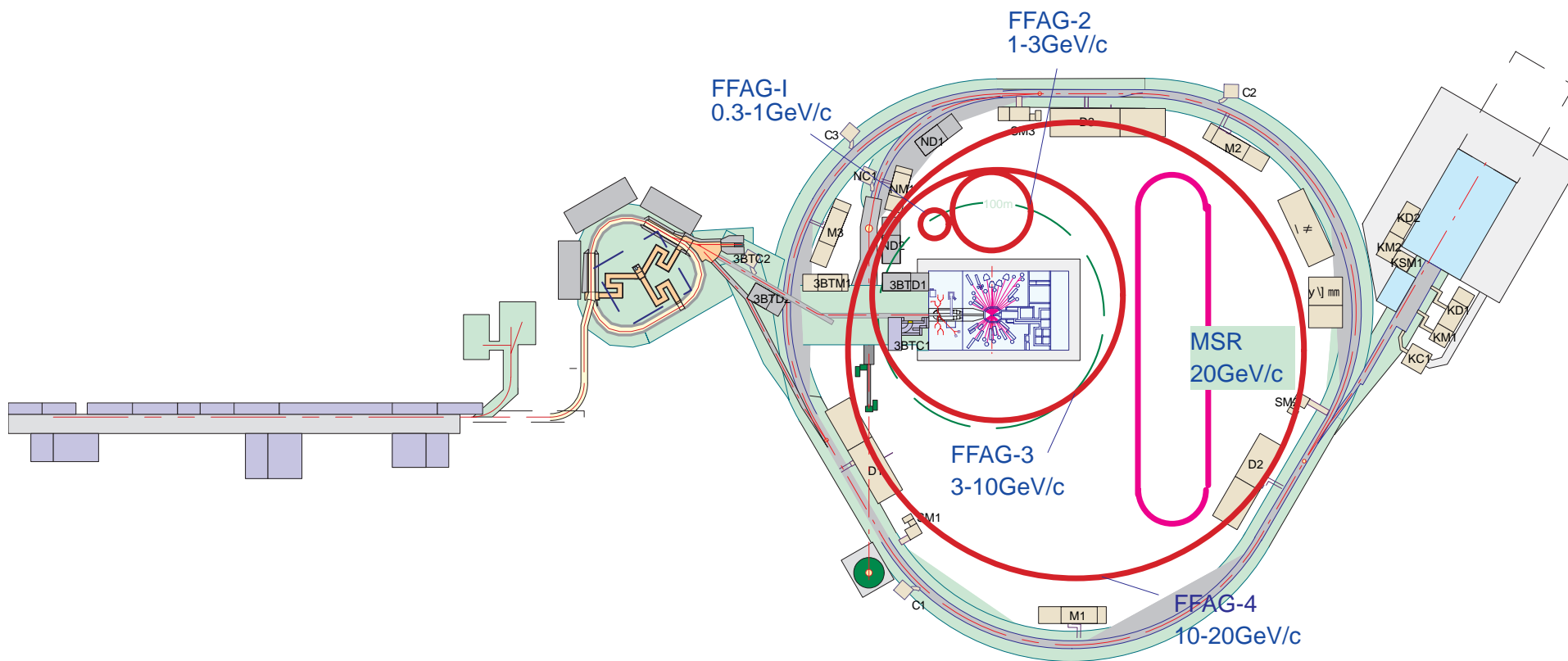
## Scaling FFAGs



- The NuFactJ scheme
- Scaling FFAGs only for entire neutrino factory, from capture to (not including) storage ring
- 4 stages, 0.3–1 GeV/ $c$ , 1–3 GeV/ $c$ , 3–10 GeV/ $c$ , 10–20 GeV/ $c$
- Idea: this may be inexpensive
  - ♦ Avoids the entire front end
- Scaling FFAGs can have large dynamic aperture
  - ♦ Arbitrarily large energy acceptance
  - ♦ No resonance crossing issues
  - ♦ Will it be large enough? Nonlinearities.
- Use low-frequency RF to accelerate
  - ♦ Lots of voltage needed at low frequency
- Will analyze later

# Scaling FFAGs

## FFAGs on Tokai Campus



# Dogbone RLA



- Full linear design exists
  - ◆ Needs to be converted into real terms, costed
  - ◆ Compare cost per GeV to FFAGs
- Misalignment and gradient error sensitivity studied
  - ◆ Orbit distortion manageable with 1 mm orbit errors
  - ◆ Quad field tolerances 0.2%
- Next steps
  - ◆ Add sextupoles to get chromatics right
  - ◆ Look at beam with finite energy spread

# Tracking in Linear Non-Scaling FFAGs

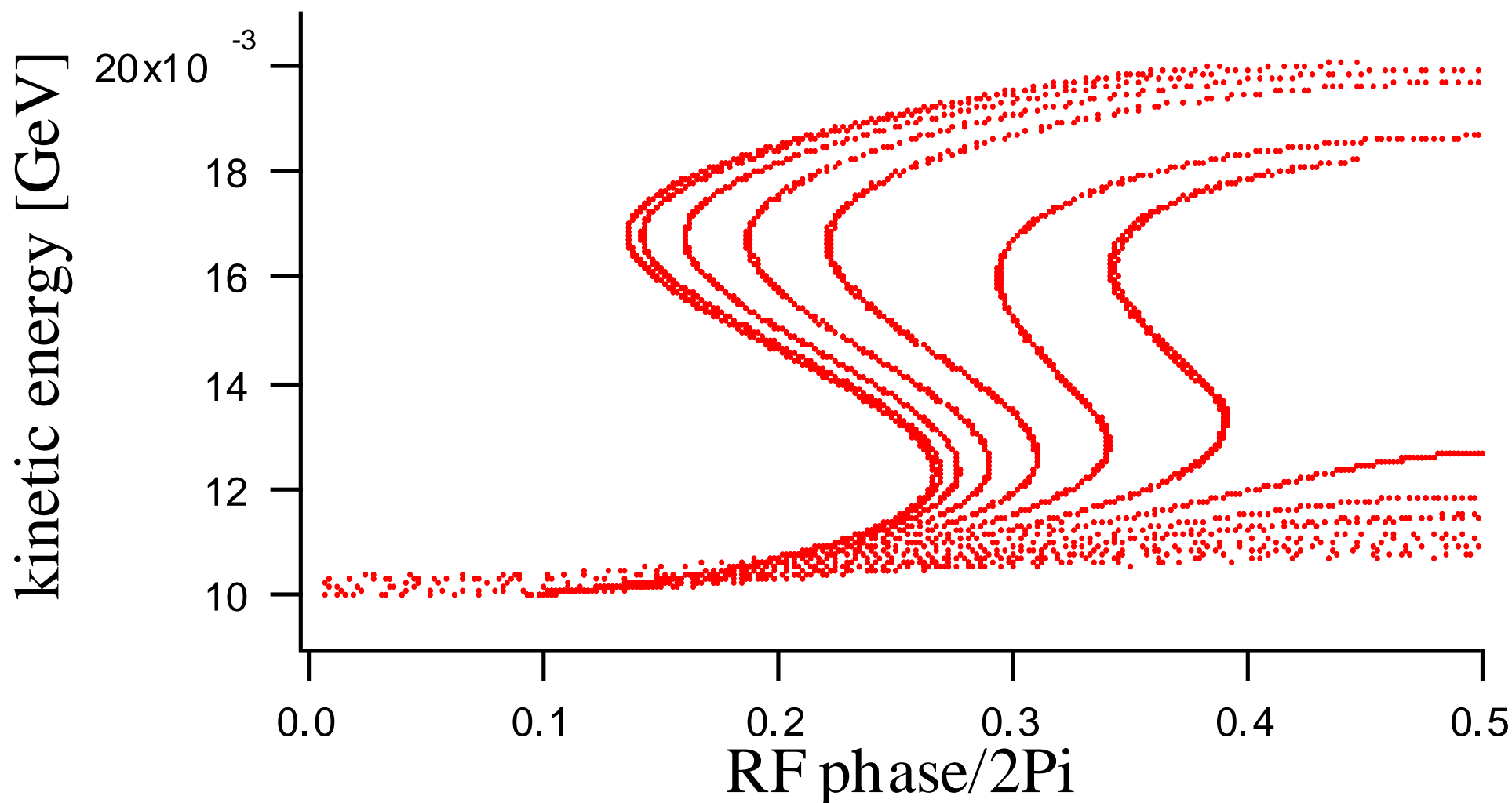
- 6-D tracking studies have begun on linear non-scaling FFAGs (Machida, Méot, Lemeut). Most codes can't handle FFAGs well.
- With real acceleration, particles with high transverse amplitude aren't accelerated properly
  - ◆ Not a problem with uniform acceleration (what we tested before)
  - ◆ Low transverse amplitudes are fine
- Cause: time of flight depends on amplitude
  - ◆ Palmer discovered this long ago, but we didn't realize the consequences
  - ◆ Can predict the dependence:

$$\frac{dT}{dJ} = -2\pi p \frac{d\nu}{dE}$$

- ◆ No effect in scaling FFAGs!

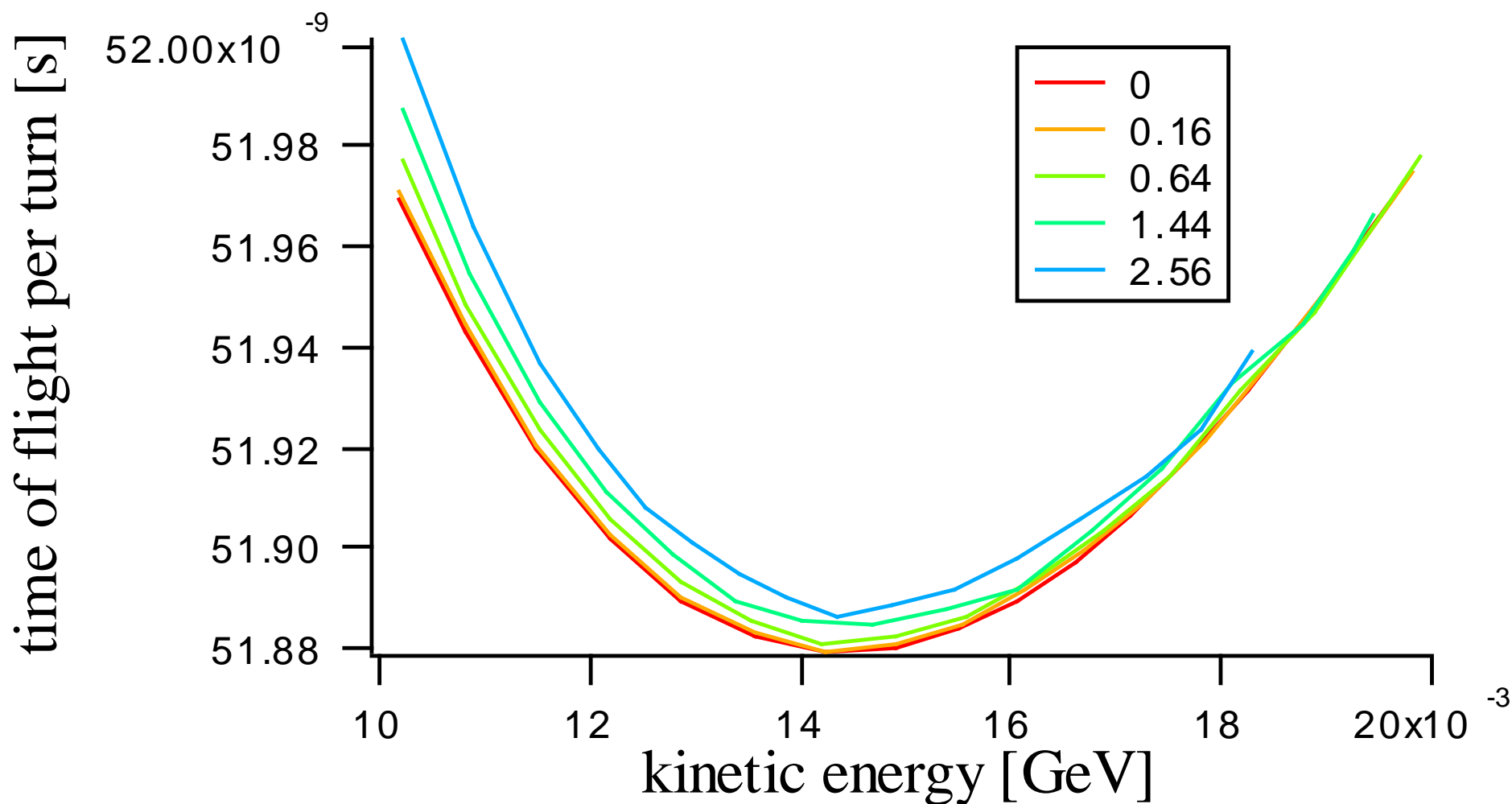
# Time of Flight Dependence on Amplitude

## Different Transverse Amplitudes



# Time of Flight Dependence on Amplitude

## Time of Flight Curves



# Tracking in Linear Non-Scaling FFAGs

## Distribution Choice



- Effect creates problems for simultaneously large transverse and longitudinal amplitudes
- Choice of distribution matters a lot

- ◆ Ellipsoidal:

$$\frac{2J_x}{A_x} + \frac{2J_y}{A_y} + \frac{2J_z}{A_z} \leq 1$$

★ if amplitudes are large in one plane, they are small in the other

- ◆ Tensor product

$$\frac{2J_x}{A_x} \leq 1$$

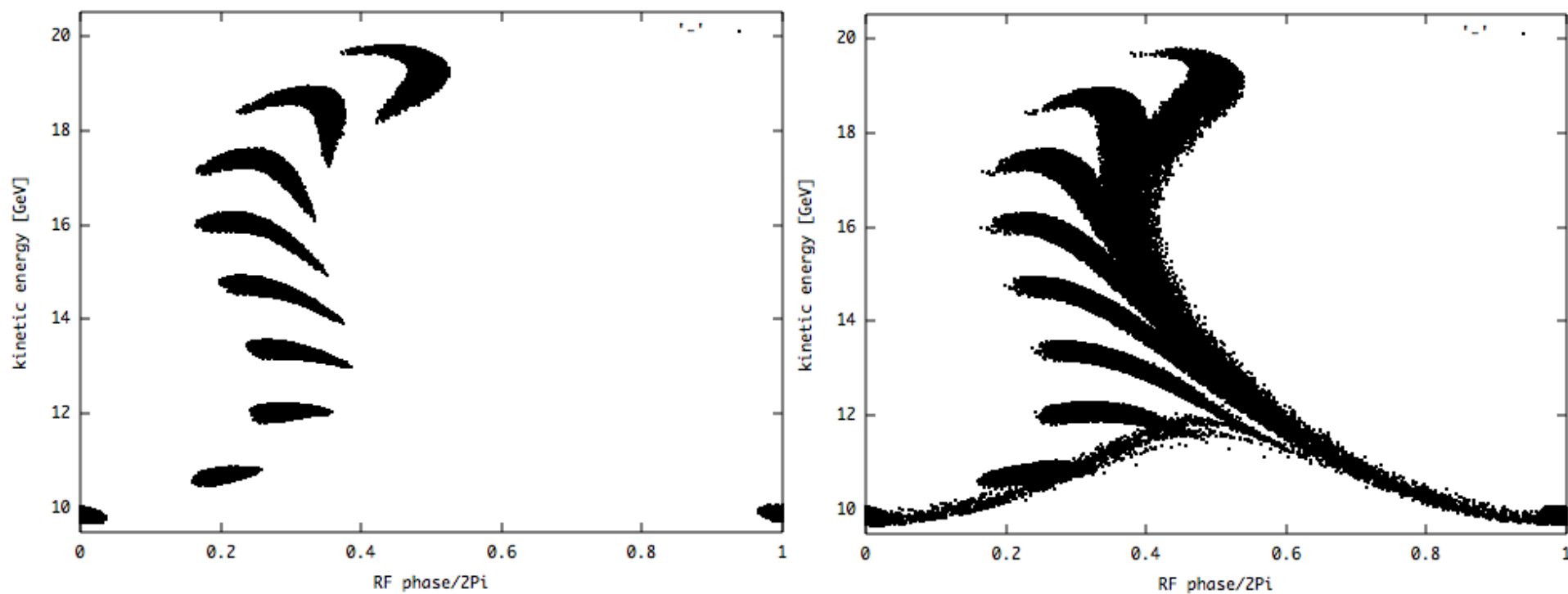
$$\frac{2J_y}{A_y} \leq 1$$

$$\frac{2J_z}{A_z} \leq 1$$

- ★ Amplitudes can be simultaneously high in all planes
- ★ Equivalent problems to ellipsoid with 3x larger acceptance

# Tracking in Linear Non-Scaling FFAGs

## Tracking with Different Distributions



# Tracking in Linear Non-Scaling FFAGs

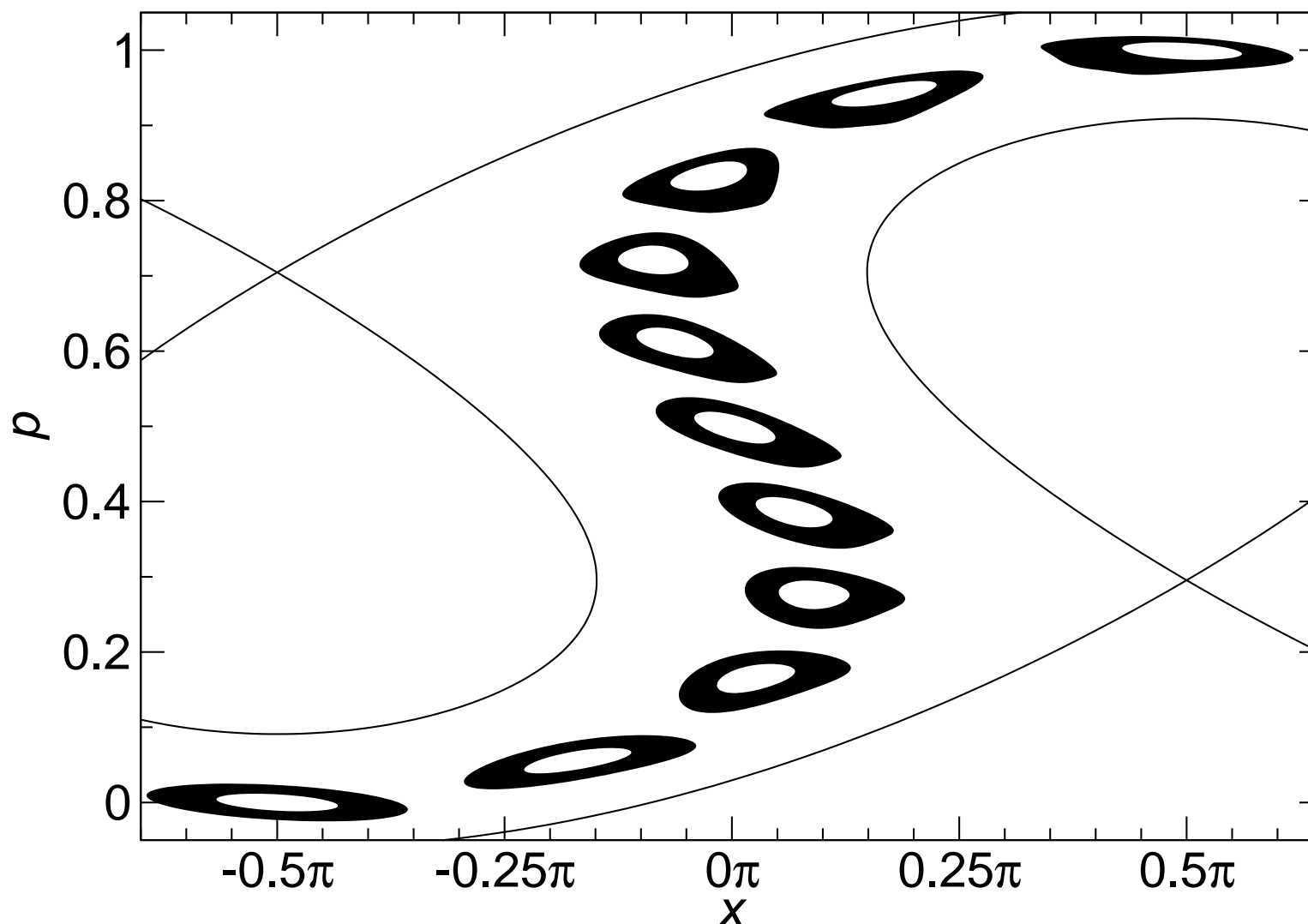
## Time of Flight Dependence on Amplitude



- Different amplitudes follow different channels in longitudinal phase space
  - ♦ Channels may not overlap
- How will we address the problem?
  - ♦ Adjust machine parameters to open up the channel more
    - ★ More voltage
    - ★ Longer ring
    - ★ Higher harmonic RF
    - ★ Costs money
  - ♦ Adjust phase space more carefully to optimize what we have
    - ★ Current model assumes that time of flight is perfectly parabolic
    - ★ Find best area of overlap (right now, using optimum for low amplitude)

# Tracking in Linear Non-Scaling FFAGs

## Longitudinal Phase Space Channel



# FFAG Electron Model



- Linear non-scaling FFAGs have never been built
- Create an inexpensive model of a linear-nonscaling FFAG
- In the last year we have
  - ◆ Refined the experimental goals of the machine
  - ◆ Settled on lattice specifications
  - ◆ Begun to look at hardware

# FFAG Electron Model

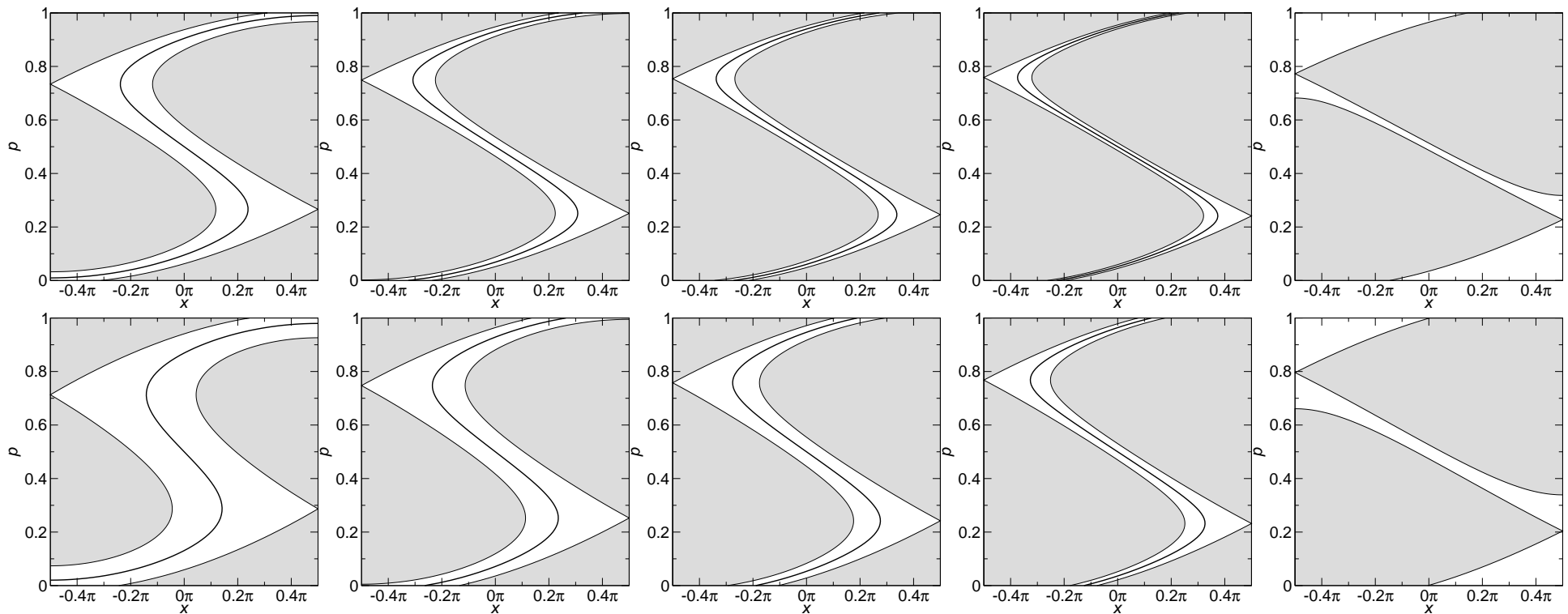
## Fixed Frequency Longitudinal Dynamics



- Accelerate up an  $S$ -shaped channel in phase space
  - ◆ Channel shape governed by time of flight dependence on energy
  - ◆ Time of flight dependence governed by transverse lattice
- Insure channel is wide enough to give acceptable distortion
- Varying machine parameters does two things
  - ◆ Pinches off the phase space channel, or makes it larger
  - ◆ Changes how energy and RF phase vary as you accelerate

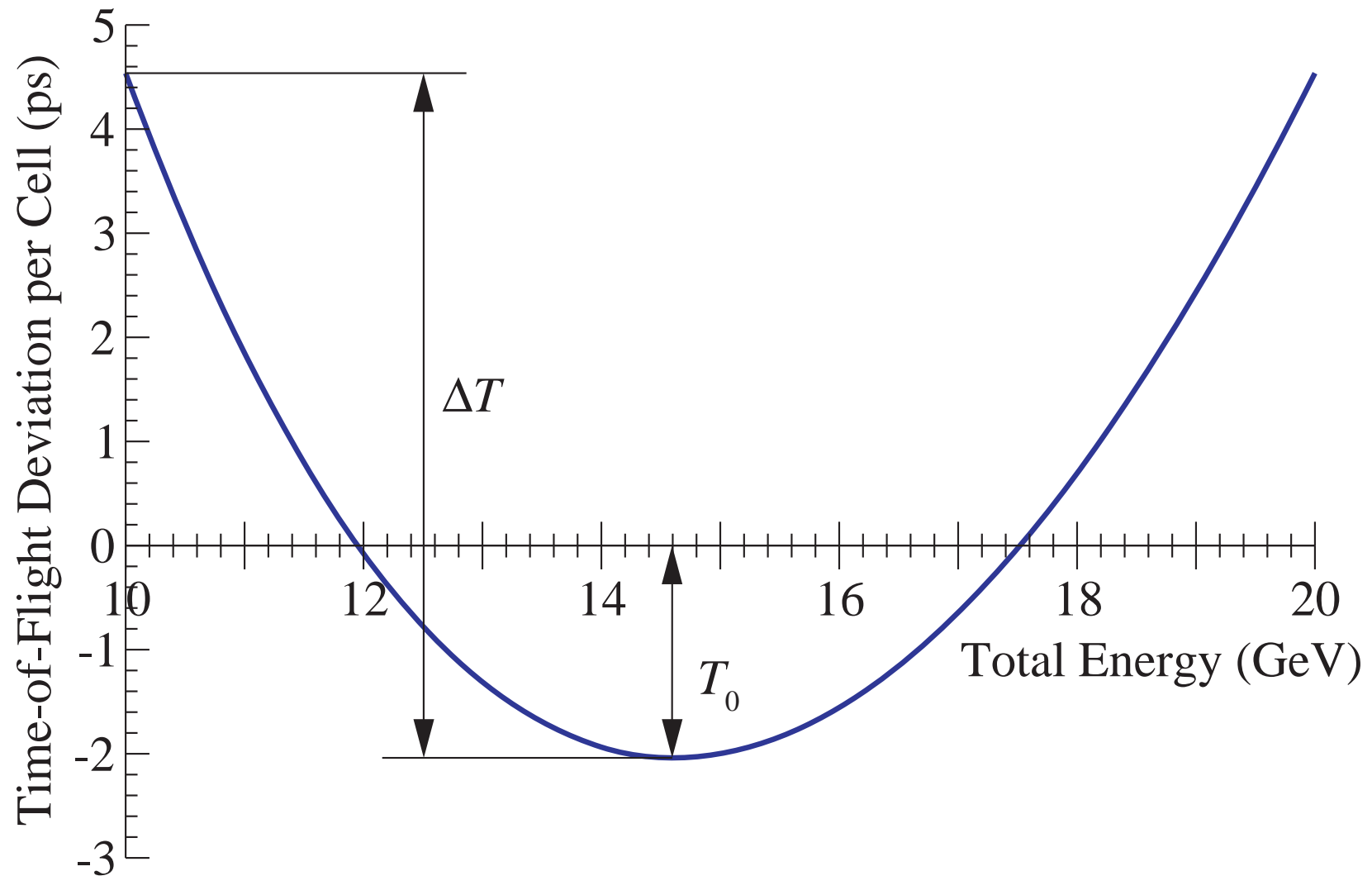
# FFAG Electron Model

## Longitudinal Phase Space



# FFAG Electron Model

## Time of Flight



# FFAG Electron Model

## Longitudinal Dynamics: Things to Study



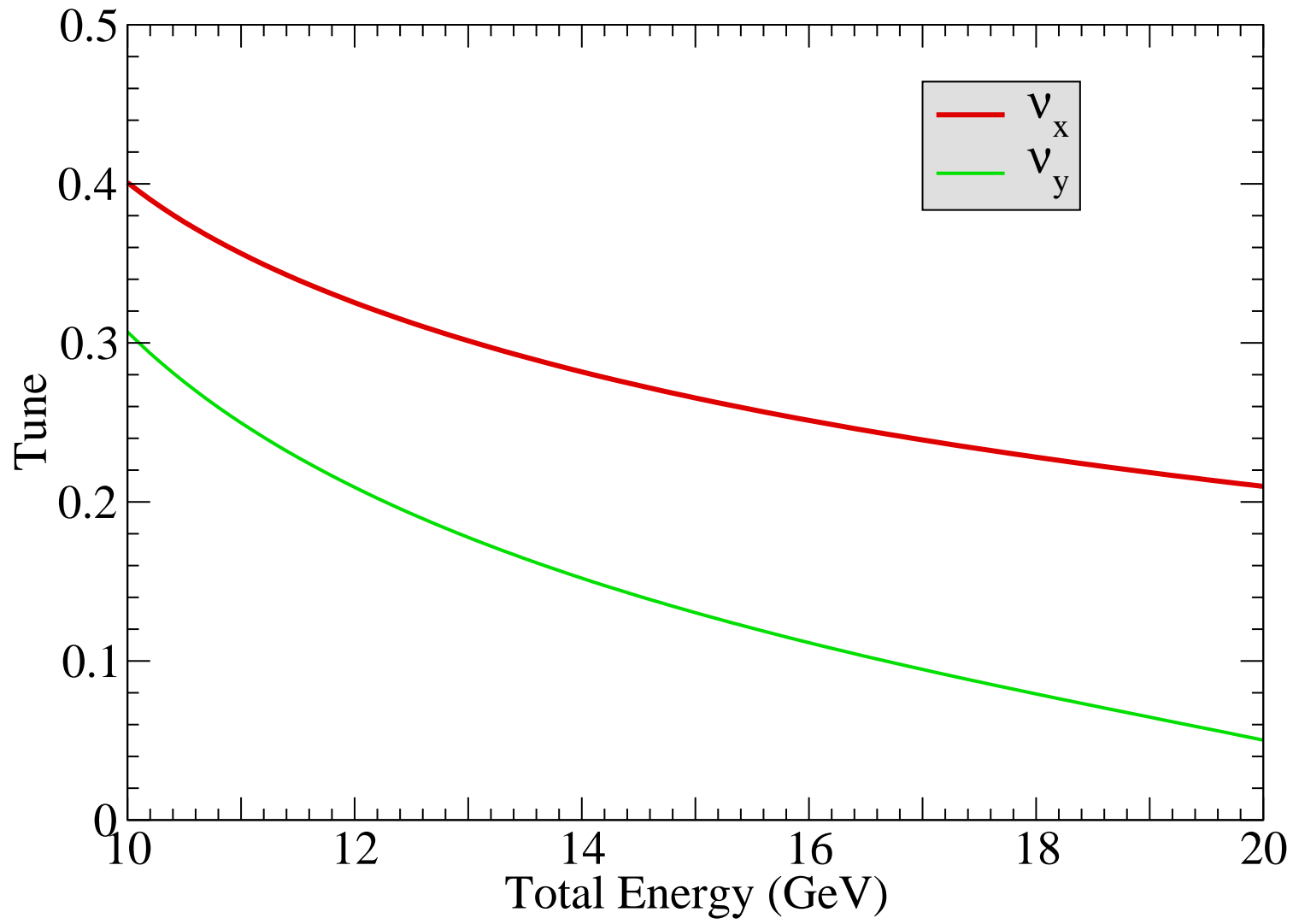
- As we vary machine parameters, do we get the expected behavior?
  - ◆ Do we lose transmission at the expected parameter values?
  - ◆ Is the emittance growth what we predict?
- The horizontal lattice determines the time of flight behavior
  - ◆ Do we get the predicted time-of-flight behavior as a function of energy?
- Effect of errors on transmission, longitudinal emittance growth
  - ◆ Phase errors in cavities
  - ◆ Lattice errors (as they affect time of flight)

# FFAG Electron Model Resonance Crossing



- During acceleration, we cross large numbers of (hopefully) weakly-driven “resonances”
- Result is emittance growth and/or beam loss
- In fixed-frequency acceleration: rate of resonance crossing depends on energy
- Resonance crossing will depend on tune/energy profile

# FFAG Electron Model Tune Profile



# FFAG Electron Model

## Resonance Crossing: Things to Study



- As we vary the resonance crossing rate (overall acceleration rate), do we get expected growth rates/losses?
- As we vary the tune range, how does the emittance growth vary? Check predictions.
- As we vary  $b$ , which changes where the high and low acceleration rates are, how does the emittance growth change?
- Introduce magnet displacements and field errors; how does this affect the emittance growth?
- Introduce low, variable-frequency RF system to study
  - ◆ Uniform rate of crossing resonances
  - ◆ Slower resonance crossing rates than we can have with the high-frequency system.

# FFAG Electron Model Simulation



- Much of this program is a verification of results obtained through simulation
  - ◆ But we want to test how varying the parameters of a muon FFAG will affect its performance
  - ◆ We of course want to address the issue of whether it works at all!
- We must be able to simulate the full system
  - ◆ Full 6-D
  - ◆ Magnet end fields
  - ◆ Arbitrary magnet displacements
  - ◆ Correct handling of RF timing
- Real machines will have these same simulation requirements
- If results do not match simulation, our task should be to determine what went wrong in the simulation

# FFAG Electron Model

## Hardware Requirements



- To test parameter space of longitudinal dynamics, for fixed transverse lattice
  - ◆ Vary cavity frequency (part in  $10^3$ : probably straightforward, but significant hardware required)
  - ◆ Vary cavity voltage (factor of 4 to 6: easy, since low voltages)
  - ◆ Vary individual cavity phases (with relatively high precision)
- To see the effect of the transverse lattice on the longitudinal dynamics (i.e., vary the parabola)
  - ◆ Independent variability of dipole and quadrupole components of the magnets
  - ◆ Without both components variable, the tune profile cannot be decoupled from the parabola centering

# FFAG Electron Model

## Hardware Requirements (cont.)



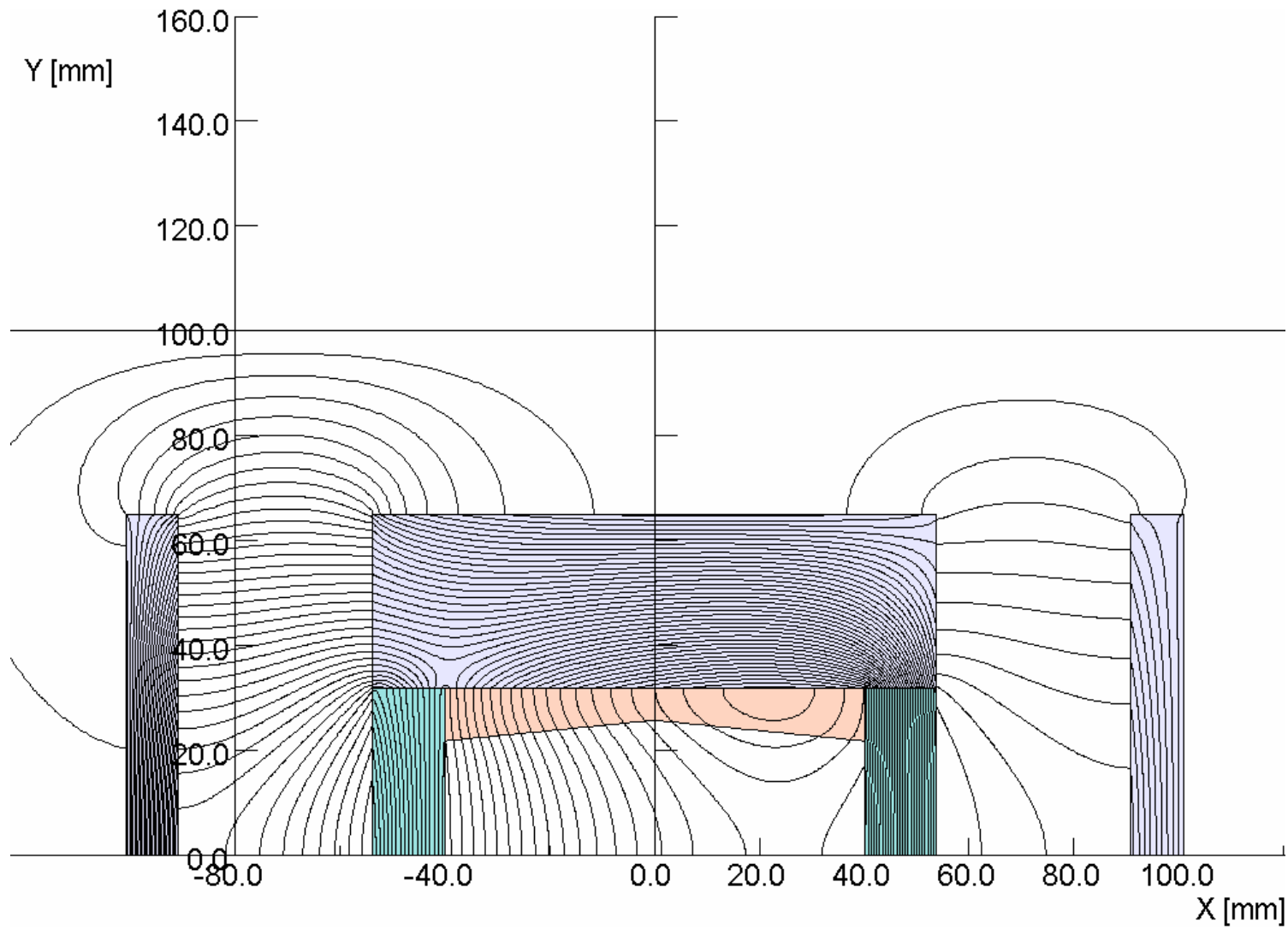
- Resonance crossing
  - ◆ Requirements as above
  - ◆ Ability to adjust magnet positions to study displacement errors
  - ◆ Individual control of magnet strengths to study gradient errors
- Without independent control of quadrupole and dipole
  - ◆ Difficult to look independently at certain effects (tune profile, parabola shape, etc.). Effects are coupled together.
  - ◆ Still will be doing simulation verification
  - ◆ Longitudinal RF parameters can still be explored thoroughly
  - ◆ Can still look at resonance crossing rate
- Lower-frequency RF system for second stage

# Magnet Designs

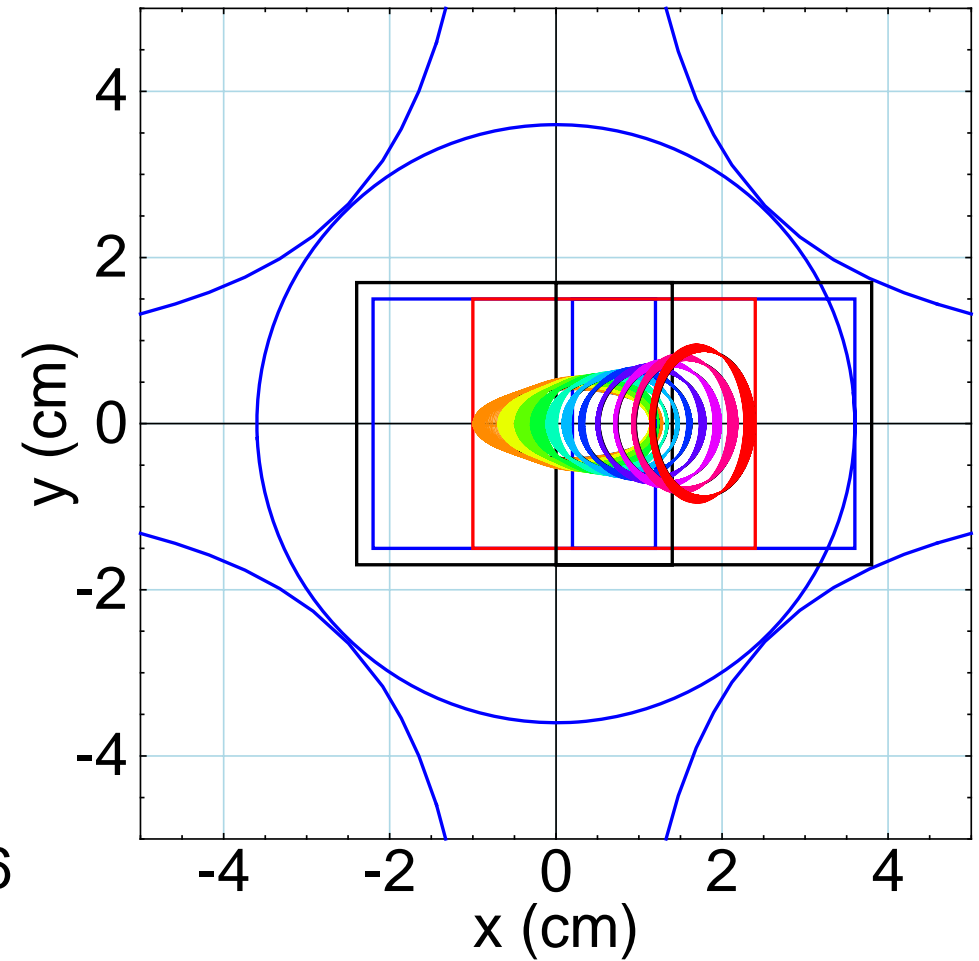
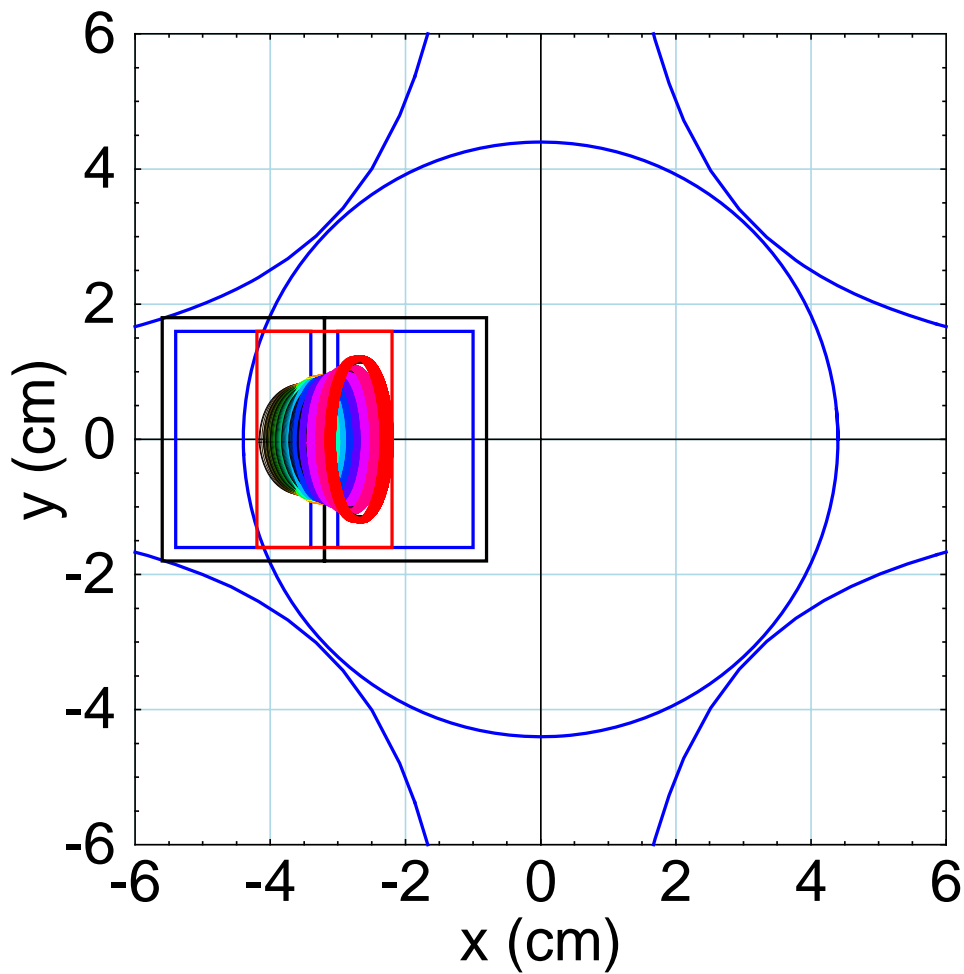


- Gradient dipole
  - ◆ Can't independently vary dipole and quadrupole
- Shifted quadrupoles
  - ◆ Vary dipole by moving the magnets
  - ◆ For D, use mirror plate
  - ◆ Potential problem: large physical aperture (end fields)

# Gradient Dipole Design



# Shifted Quadrupoles



# FFAG Electron Model Diagnostics



- To measure these effects, need extensive diagnostics
- Longitudinal
  - ♦ Can do initial experiments (e.g., look for point of pinch-off) simply by having energy distribution at extraction or in ring
  - ♦ To get longitudinal emittance growth, need more detailed diagnostics
- Resonance crossing
  - ♦ Need relatively accurate transverse emittance measurement
- Ability to extract is probably important for detailed measurements

# FFAG Electron Model

## Determining Parameters



- Rate of resonance crossing is (roughly) the product of cells and turns (cell-turns)
  - ♦ Muon acceleration: between 500 and 1500 cell-turns
  - ♦ More cell-turns requires a larger machine, so try for the low end: 500 cell-turns
- Match other parameters of muon machines
  - ♦ Factor of 2 in energy
  - ♦ Low-energy tunes:  $\nu_x = 0.39$ ,  $\nu_y = 0.27$
- Pole tip field limitation of magnets
- $a = qV/(\omega\Delta T\Delta E)$ : choose 1/12, to have reasonably-sized channel
  - ♦ Can make larger if we so desire: voltages are small
- Doublet cells
- Want similar angles and fraction of aperture filled: about 3 mm normalized emittance

# FFAG Electron Model

## Resulting Parameters



- RF frequency choice: with 0.2 T pole tips, 1.3 GHz requires 42 cells, 3 GHz requires 60; choose 1.3 GHz
- Pole tip field: to get 500 cell-turns

Pole Tip Field (T)	0.1	0.2	0.3
Cells	48	42	42
Circumference (m)	23.1	15.9	14.1
Magnet Aspect Ratio (L/A)	2.1	1.3	0.9

- ◆ At 0.1 T, ring is too long
- ◆ At 0.3 T, magnet aspect ratio is bad: ends contribute too much
- ◆ Probably prefer 0.2 T or slightly below for balance
- To achieve  $a = 1/4$ , need 115 kV per cavity (every other cell has cavity), gradient 1 MV/m: EASY!
  - ◆ Issue: too much stored energy extracted if high current, but need high current for diagnostics

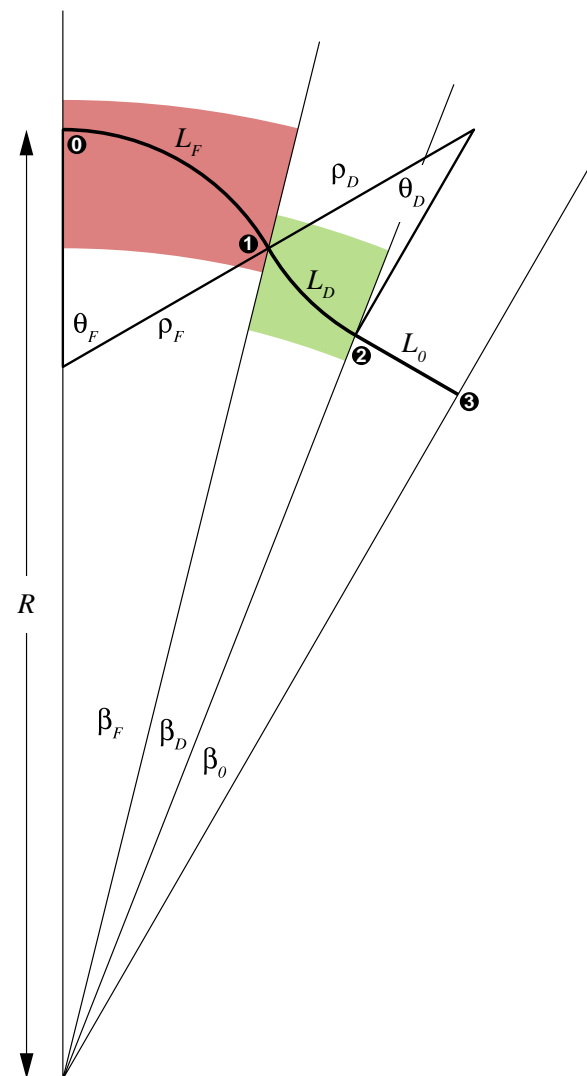
# NuFactJ Parameters

- Need a description of the field in the FFAG
- NuFactJ report: description based on arcs of sector magnets, run in SAD
- Need to convert to

$$B(r, \theta) = B_0(\theta)(r/r_0)^k$$

$B_0(\theta)$  piecewise constant

- Geometry determined, only specify fields
- For some lattices, no reasonable guess works



# My Versions of NuFactJ Lattices



- Try to fit the tunes, assuming those were chosen carefully
- Can't do this by just varying fields: degeneracy due to scaling
- Vary  $\beta_F$ ,  $B_D$ , keeping  $\beta_0$  fixed

# My Versions of NuFactJ Lattices

## Magnet Parameters and Cost



- Machine costs are huge (non-scaling FFAGs:  $\lesssim 100$  PB each stage)
- Magnet apertures are large
- Fields are very high
- Note: no cavities in cost!
  - ◆ RF systems used
    - ★ 0.75 MV/m average over ring, air gap, 5–10 MHz
    - ★ First ring may be variable frequency
      - New type of magnetic alloy core
    - ★ All this needs more careful specification, R&D, costing
  - ◆ RF cost will be a significant additional cost

# My Versions of NuFactJ Lattices

## Magnet Parameters and Cost



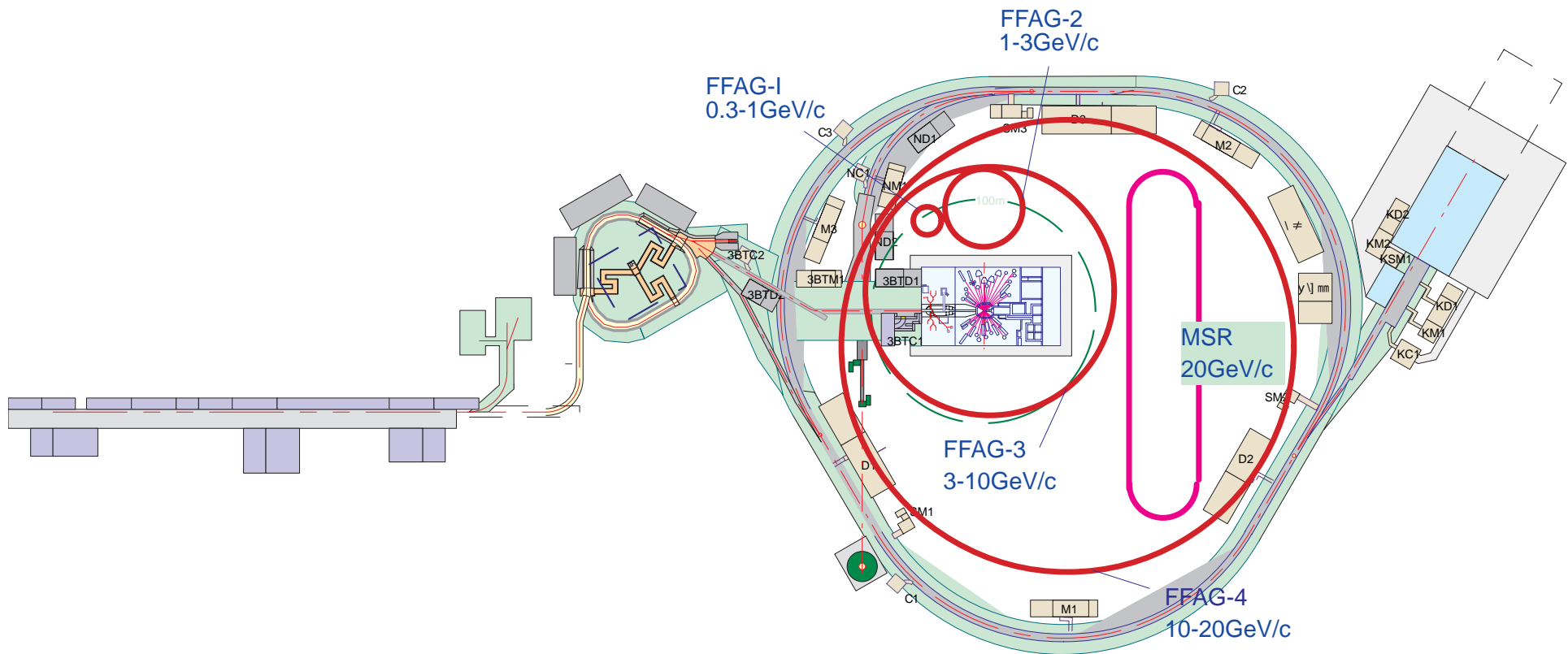
Lattice number	1	2	3	4	5	6
Cells	32	16	64	32	64	120
Average radius (m)	21	10	80	30	90	200
$L_F$ (m)	1.125	1.088	2.111	1.640	2.225	3.257
$r_F$ (cm)	58.3	75.0	54.1	59.7	52.9	45.0
$x_F$ (cm)	-35.5	-51.6	-32.9	-37.3	-34.0	-41.1
$B_F$ (T)	3.442	4.355	3.292	6.282	9.493	6.567
$L_D$ (m)	0.345	0.288	0.696	0.482	0.770	0.766
$r_D$ (cm)	52.2	67.2	48.1	52.1	47.4	41.2
$x_D$ (cm)	-40.6	-60.5	-40.4	-45.7	-41.4	-48.5
$B_D$ (T)	-3.450	-4.368	-3.387	-6.316	-9.301	-10.783
Cost (PB)	281	355	396	527	1153	1410

# My Impressions from Conversations



- These designs were just supposed to be “typical”
- Constrained to fit inside 50 GeV proton ring
- Nobody did anything beyond the SAD model
- RF systems are all R&D projects

# FFAGs on Tokai Campus



# Lattices from 2002 LBNL FFAG Workshop

- Work was done on improving the high energy (10–20 GeV/c) FFAG lattice
  - ◆ FODO lattice
  - ◆ Two versions
    - ★ Same number of cells, higher field index, smaller ring
    - ★ Larger ring, more cells even higher field index
- I ran the lattices based on a hard edge model
- Cost reduced significantly from NuFactJ design
  - ◆ Apertures and fields both much lower
  - ◆ Still high
  - ◆ Cost can be improved by increasing cells
    - ★ Need to fold decays in as usual

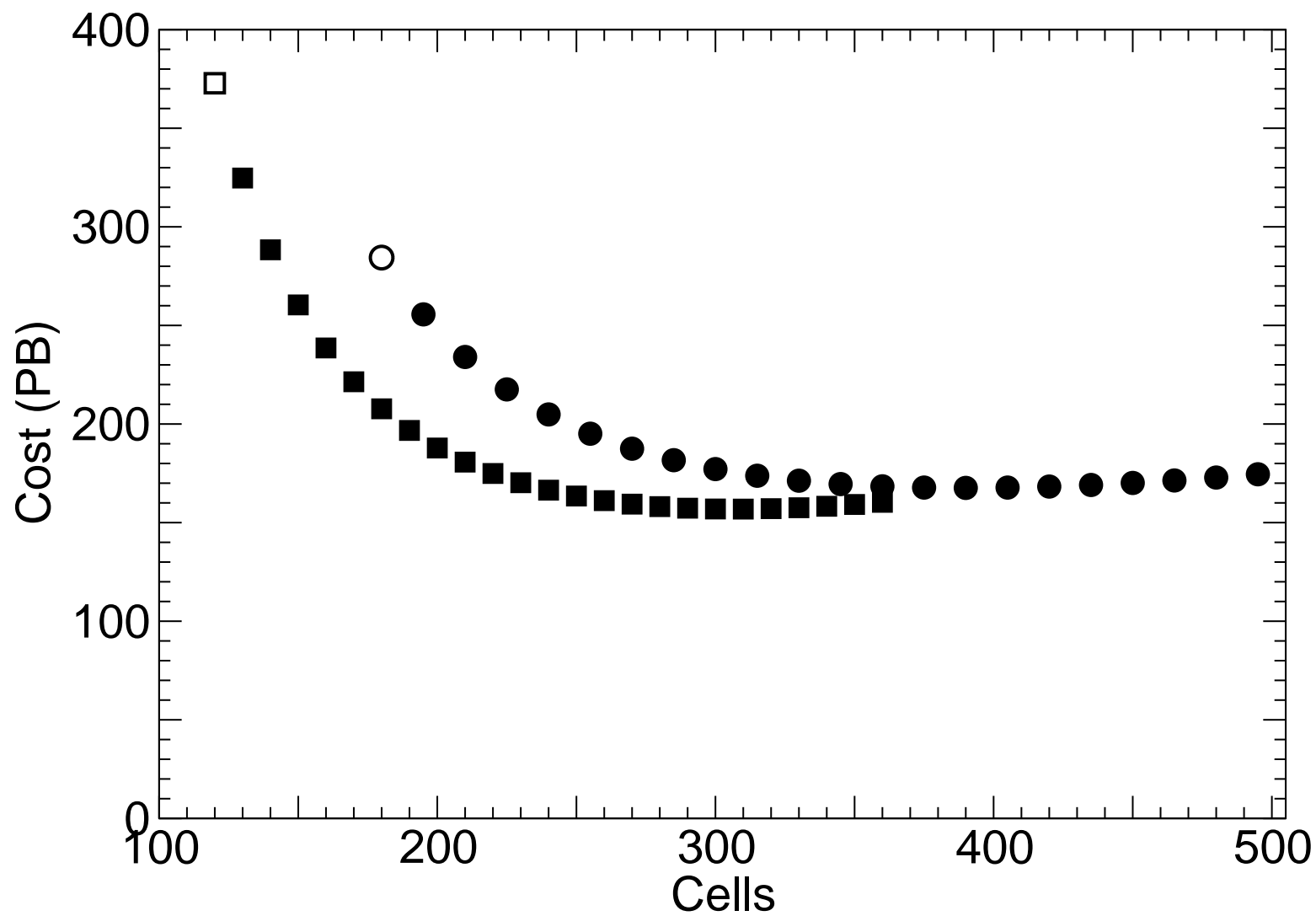
# Parameters from 2002 LBNL FFAG Workshop



Cells	180	120
Field index	670	330
Reference radius (m)	200	120
Ends (m)	0.30	0.20
D angle (deg)	0.438	0.63
D length (m)	0.93	0.92
D field (T)	5.795	7.738
F angle (deg)	0.562	0.87
F length (m)	1.36	1.42
F field (T)	-3.636	-4.857
Drift length (m)	2.35	1.97

Cells	180	120
$L_F$ (m)	1.362	1.422
$r_F$ (cm)	20.4	23.5
$x_F$ (cm)	1.8	2.0
$B_F$ (T)	7.664	9.764
$L_D$ (m)	0.928	0.918
$r_D$ (cm)	17.8	20.5
$x_D$ (cm)	-10.9	-12.8
$B_D$ (T)	-7.282	-9.560
Cost (PB)	284	373

# 2002 LBNL Lattice Cost vs. Cells



## New Lattices, not Analyzed as Yet

- There is a 10–20 GeV doublet scaling lattice (early 2003)
  - ◆ Expect cost improvement
  - ◆ Still waiting on specs for this
- Lowest energy lattice corrected to normal conducting
  - ◆ Need to work out costing for that
- New proposal by Mori: 10–20 GeV singlet spiral sector
  - ◆ Normal conducting, 100 m radius, 50 cm orbit excursion
  - ◆ Passive extraction: orbit jump

## Next Steps

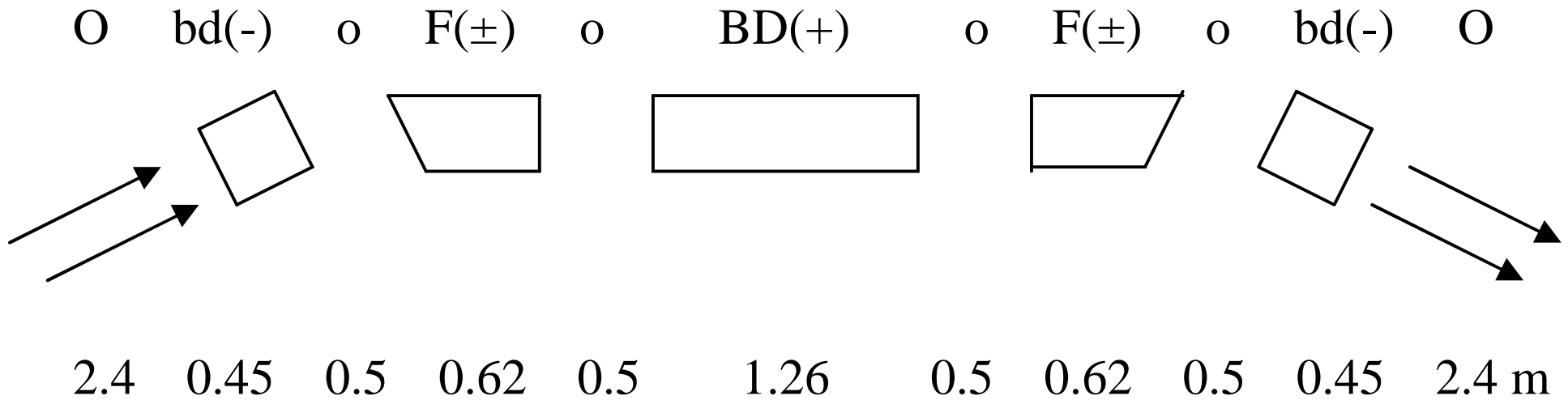


- Need to work out details of a working scheme for all stages
  - ◆ Analyze all the schemes I currently have
  - ◆ Lattices other than first and last probably need to be defined
    - ★ Optimized to some extent for cost
  - ◆ Need to work out details RF systems
- Need some costing information
  - ◆ Normal-conducting scheme at low energy
  - ◆ All RF systems
- Start to do more complete simulations

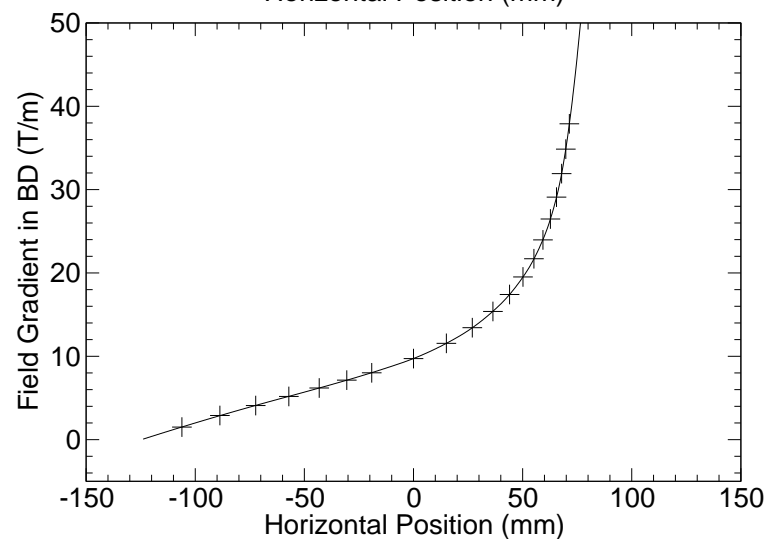
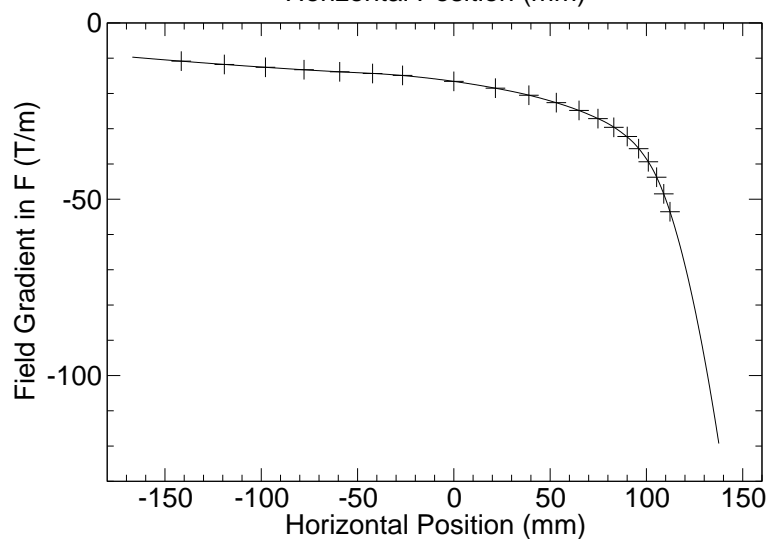
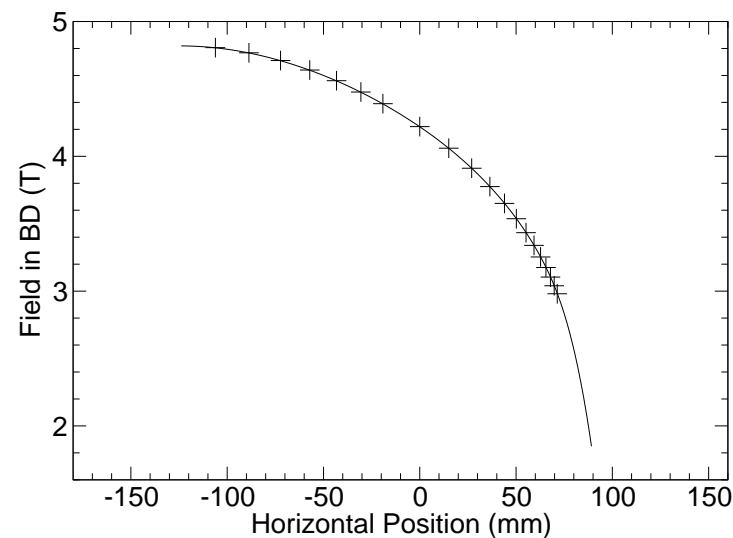
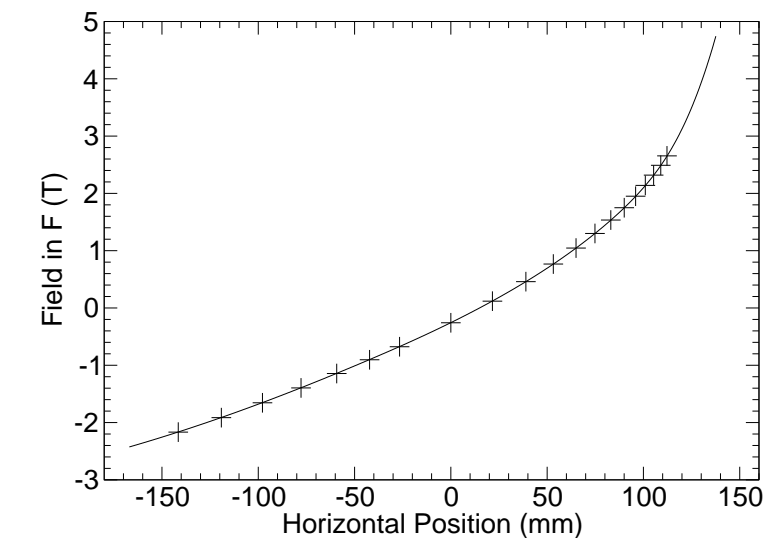
# Isochronous FFAG Scenario (Rees)

- Avoid time of flight problems: act like a linac, make machine isochronous
- Two stages: 3.2–8, 8–20 GeV
- Field description
  - ◆ Original description based on constructing multiple linear lattices, connecting appropriately
    - ★ Resulting field is nonlinear
  - ◆ I fit fields using cubic spline
    - ★ Good fit
    - ★ No excess oscillations
    - ★ Extrapolates well
  - ◆ Note highly nonlinear fields

# 5-Cell Lattice



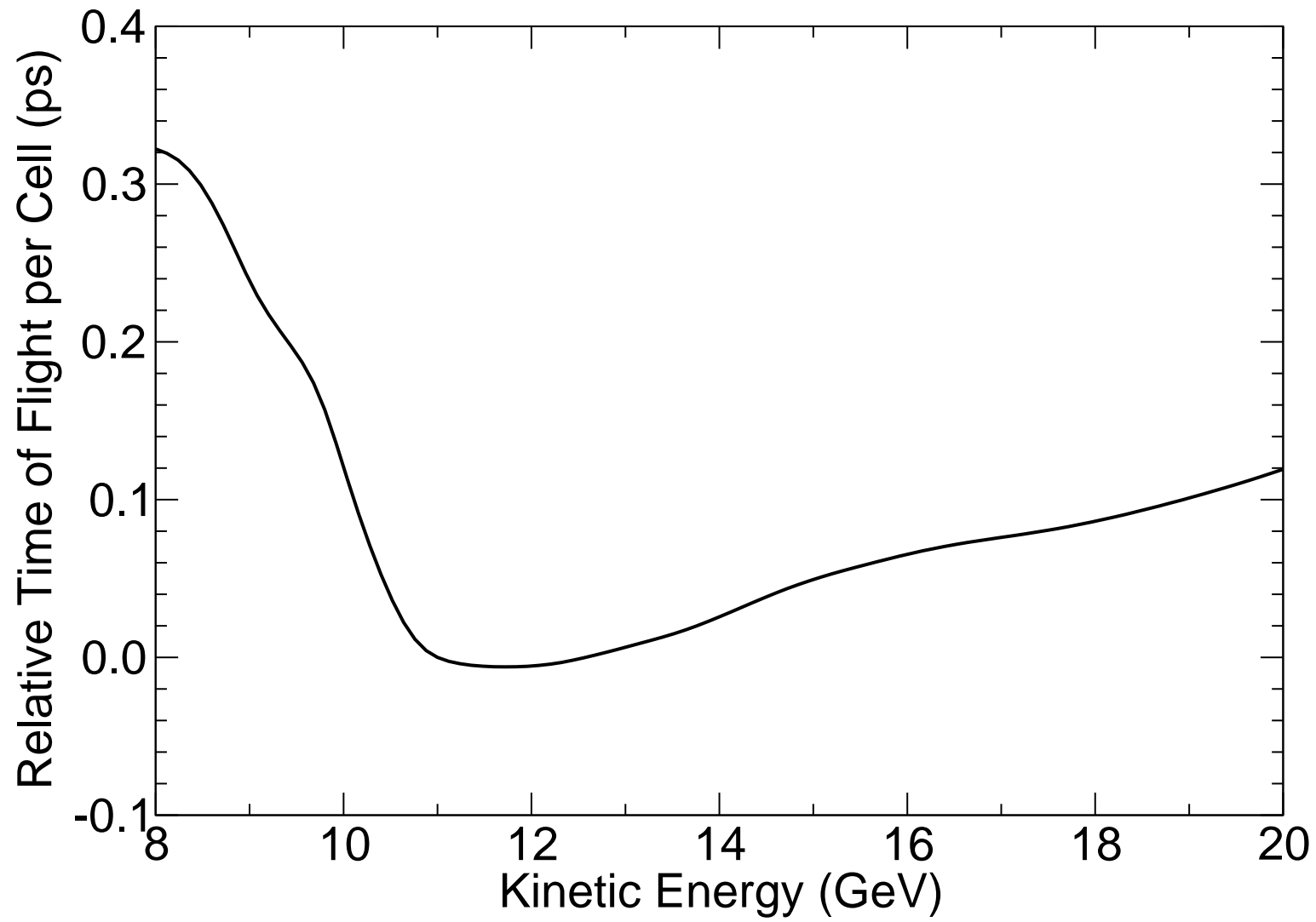
# Field Fits for Isochronous FFAG



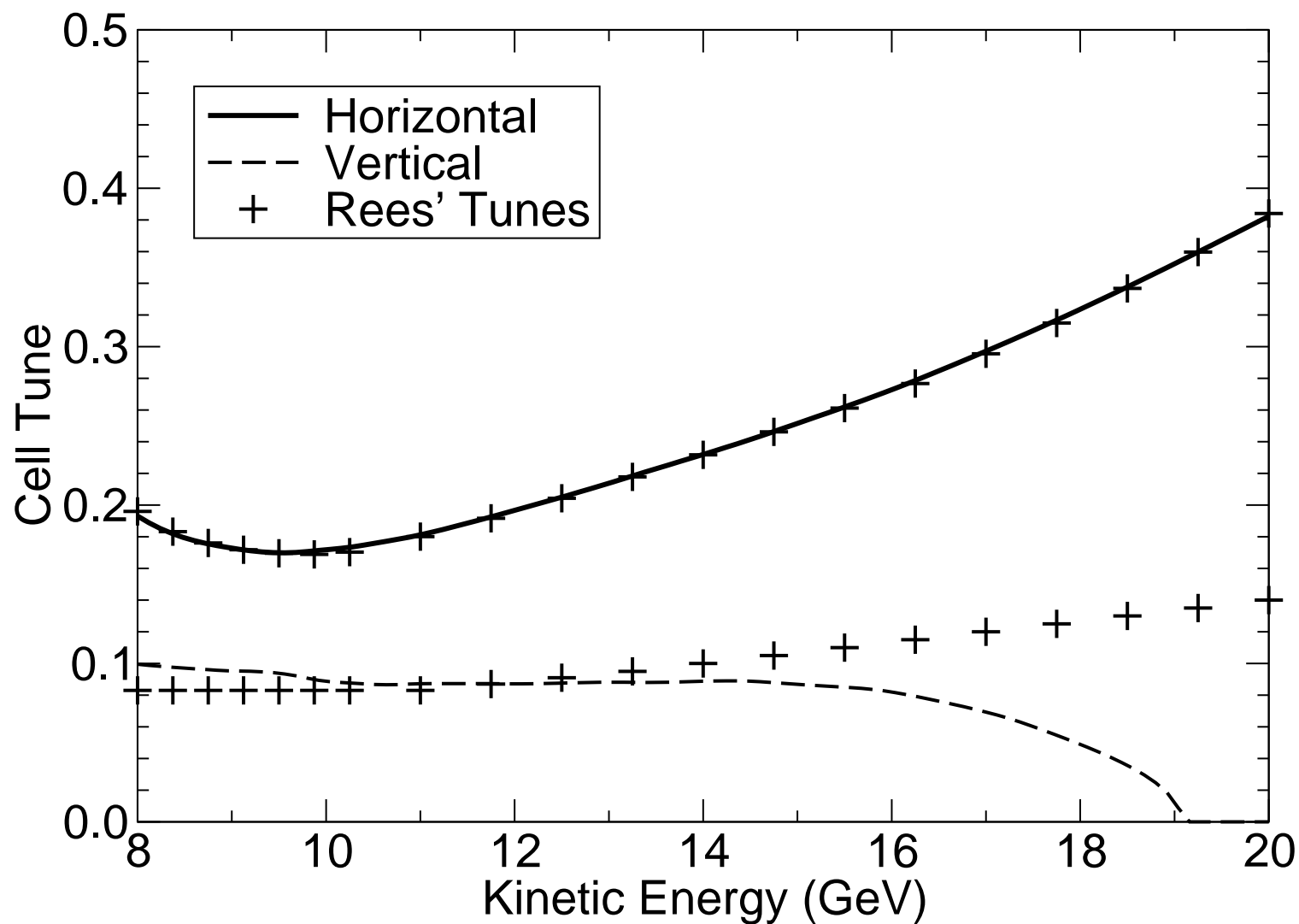
# Isochronous FFAG: Analysis

- Time of flight variation is exceptionally small
  - ◆ Factor of 10 below natural value
- In my computation, tunes go unstable at high energy
  - ◆ Possible cause: Rees uses second-order edge effect which I don't
- Tracking results (Méot)
  - ◆ Beam loss at high energy end
  - ◆ Appears to come from hitting a resonance
    - ★ Note it occurs just where I say the lattice goes unstable
  - ◆ Highly nonlinear fields at high energy could also be driving it into the resonance

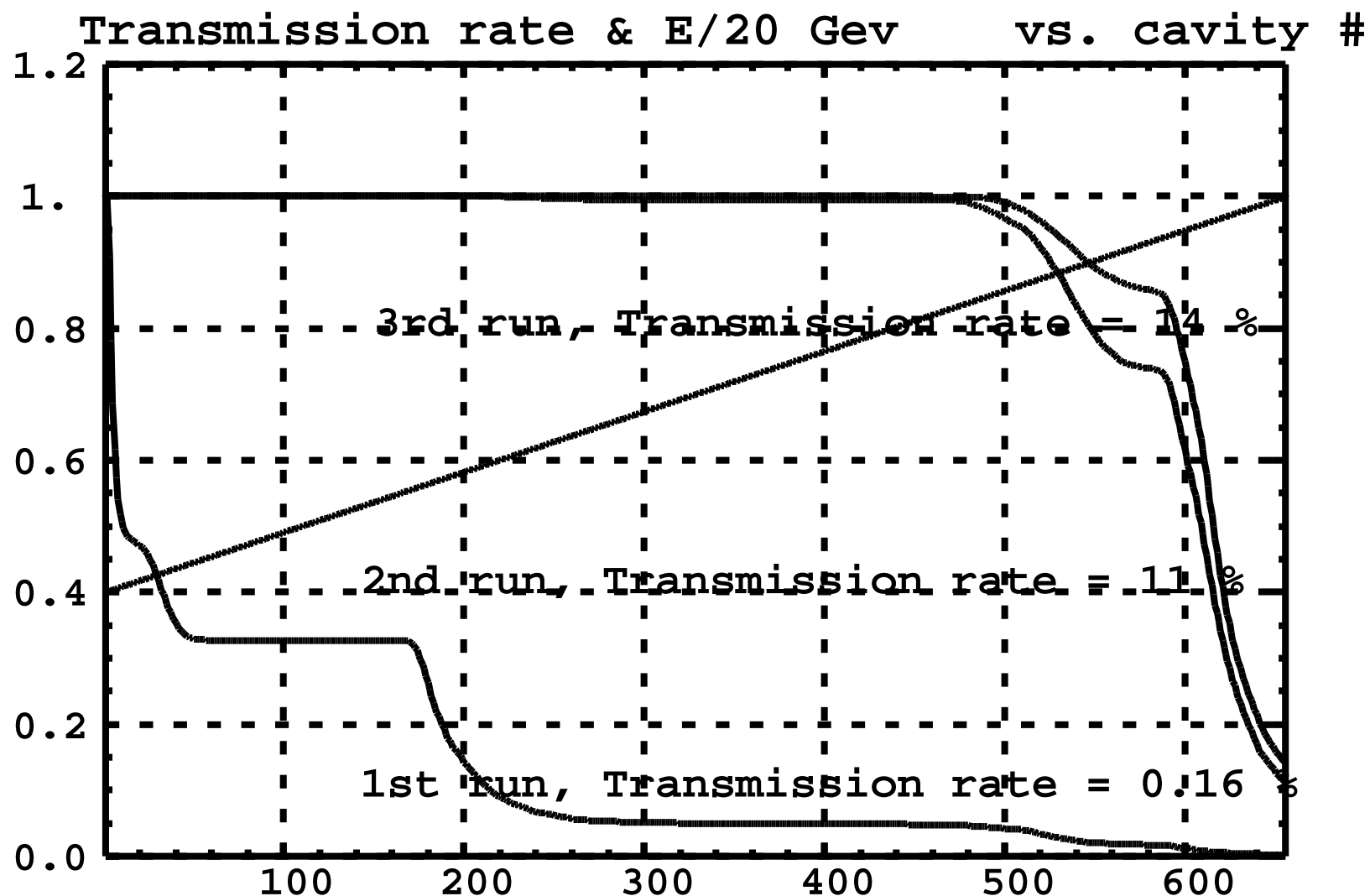
# Time of Flight in Isochronous FFAG



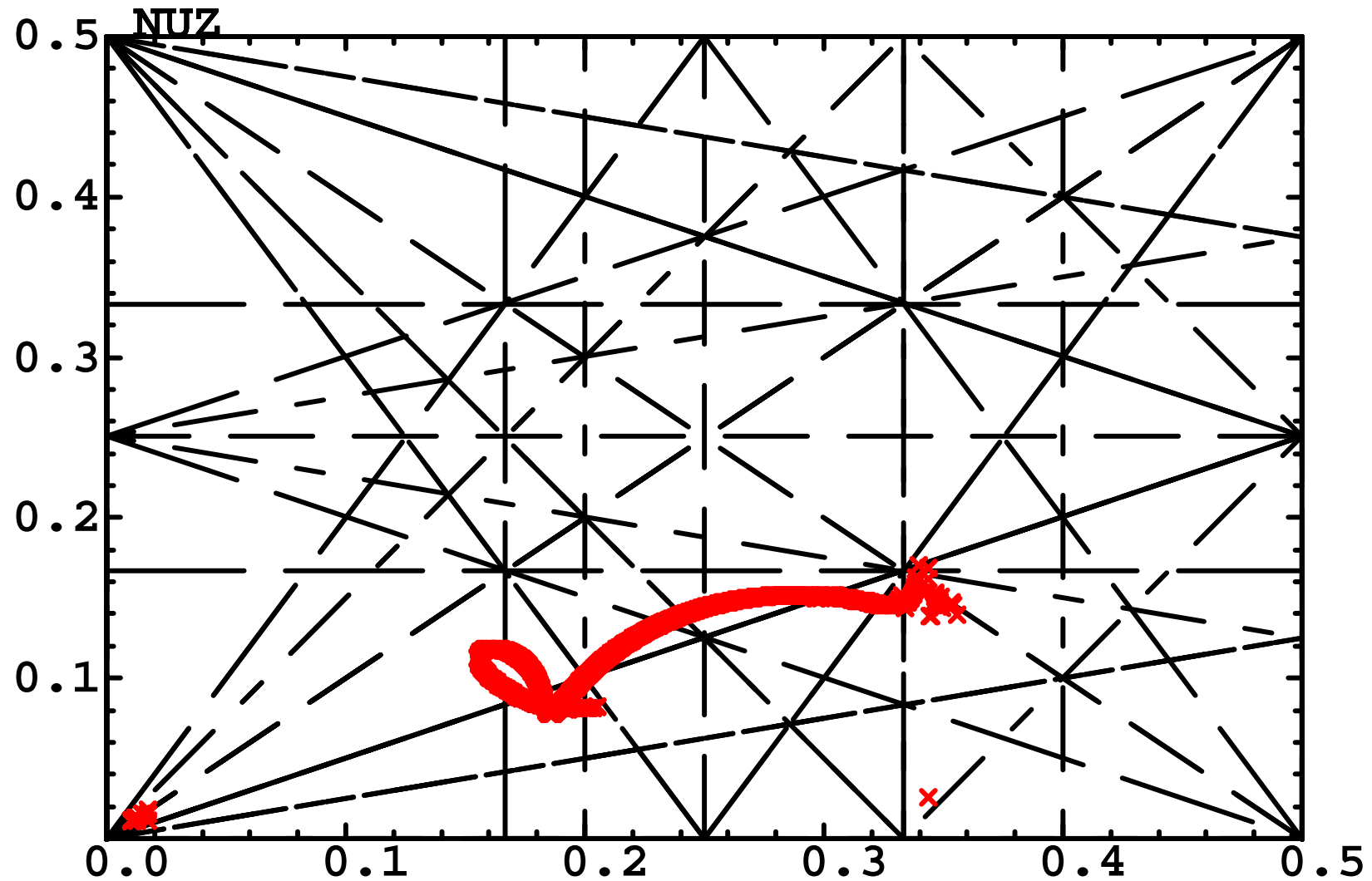
# Tunes in Isochronous FFAG



# Isochronous FFAG Beam Loss



# Isochronous FFAG Evolution in Tune Space



# Isochronous FFAG

## Observations, Recommendations



- Machine is very fussy:
  - ◆ Tiny changes in lattice (0.1% change in lengths) have substantial effect on time of flight
  - ◆ Small end effects give drastic change in tunes
- Probably related to very nonlinear fields, especially at high energy
  - ◆ Could possibly relax this: certainly room in time of flight
    - ★ Amplitude dependence of time of flight will give big contribution to TOF anyhow
  - ◆ Could consider reducing energy range
- Notice “wiggles” in time of flight
  - ◆ More automated design method would take this out
  - ◆ May also improve performance

# Isochronous FFAG Tasks



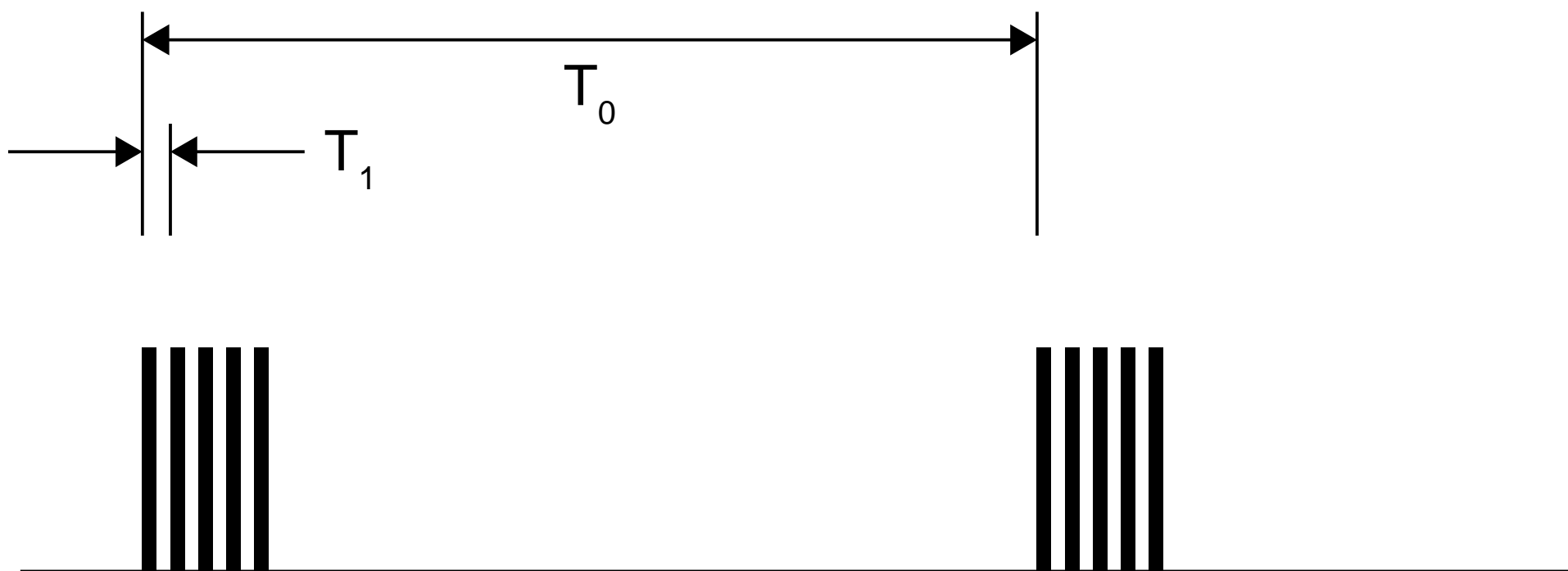
- Next, try to do some costing
  - ◆ Since lattice unstable at high energy, will have to make guess for beam sizes there.
- Still want to add insertions
  - ◆ Short cells in arcs, longer cells in straights to fit RF
  - ◆ May reduce cost
  - ◆ Matching tricky
  - ◆ Get lattice without insertions working first

# New Bunch Train Scheme

- A solid target would like to see as few particles as possible
- Fewer particles per bunch in the proton driver makes things easier
- Acceleration can't run with too high of a rep rate
  - ◆ Cavities throw away unused stored energy
  - ◆ Leads to high average power
- Solution: use sub-trains
  - ◆ There is a time period for the proton driver to accelerate several bunches:  $T_0$
  - ◆ The bunches hit the target, separated by a time  $T_1$ 
    - ★  $T_1$  much less than the (superconducting) cavity fill time
    - ★ Avoids increase in average power

# New Bunch Train Scheme

## Bunch Train Timing



# New Bunch Train Scheme

## Acceleration Requirements



- Acceleration: must replenish the stored energy in the cavities before the next bunch comes
  - ◆ 5 bunch trains, 4 MW proton driver,  $T_0 = 1/50$  Hz, existing cavities in 10–20 GeV FFAG:
  - ◆  $Q_L = 10^6$ , 1 MW limit per cavity cell, allows  $T_1 = 45 \mu\text{s}$
  - ◆ At existing power levels (0.5 MW per cavity cell), requires  $T_1 = 135 \mu\text{s}$
  - ◆ Average power required far from being proportional to number of trains
- Beam loading reduced drastically
  - ◆ Certainly needed to be addressed: different bunches in train had different energies
  - ◆ This is not the only solution
- Storage ring a challenge

# Conclusions



- We have an RLA lattice up to 5 GeV, and analysis is proceeding.
- We are trying to compare different FFAG systems
  - ◆ Linear non-scaling FFAGs are having problems with large amplitude particles. Know how to address, additional costs.
  - ◆ Scaling FFAGs look costly, but optimization seems to be helping that. RF may be an issue.
  - ◆ Isochronous FFAGs have serious dynamic aperture problems, but more work may address this.
- We have and are continuing to develop a good experimental plan and design for a model to study linear non-scaling FFAGs
- We have a new idea for a scheme for bunch trains, which is a nice way to address the beam loading issue in acceleration.